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Energy Analysis Of Co2-Based Demand Controlled Ventilation And Economizer For Air Source Heat Pump In Schools

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Energy Analysis of CO_2-Based Demand Controlled Ventilation and Economizer for Air Source Heat Pump in Schools

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Biographical Sketch

Nihal Al Raees was born on March 12, 1965 in Baghdad, Iraq. In 1988, she earned the Bachelor Degree in Architectural Engineering from Baghdad University Iraq. During 1988-2000, she worked as an architect engineer in the National Center for Engineering Consultancy, Baghdad, Iraq. In 1989 she won the first place of designing Belat Al Shuhada'a School and the second winner by designing a Private Masgid in the notional competitions in Baghdad, Iraq. During 2000-2006, she worked for Ibnkaldon Company doing engineering consulting. Many projects were mainly about health care, school, engineering projects and private houses. In January 2011, she started her Master program at North Carolina Agricultural and Technical State University.

Dedication

To my parents…..

My dear husband……..

My family……

And all who support and believe in me…….

Acknowledgements

My truthful appreciation is to Dr. Nabil Nassif, who has been my advisor as a graduate student. Dr. Nassif started with me from the first step of understanding an HVAC system, to the point of researching to improve this system. He also taught me that research takes hard work, dedication, and determination. All his effort and belief in my potential helped me go forward in my research process.

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List of Abbreviations

IAQ	Indoor Air Quality
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
HVAC	Heating, Ventilation, and Air Conditioning
DCV	Demand Control Ventilation
CO_2	Carbon Dioxide
CO_2-DCV	Carbon Dioxide base Demand Control Ventilation
SDW	Schematic Design Wizard
DDW	Detailed Data Wizard
ASHP	Air Source Heat Pump
DOAS	Dedicated Outdoor Air System
DV	Displacement Ventilation

Abstract

This study discusses the application of the CO_2-based demand-controlled ventilation (CO_2-DCV) strategy along with an economizer for air source heat pumps in schools. An investigation was performed of their impact on annual energy consumption, and the potential savings achieved in different USA locations was determined. The study includes detailed energy analysis on an existing middle school through entire building energy simulation software. The simulation model is first calibrated and checked for accuracy using the actual monthly utility data of the school. Second, this model is used for saving calculations due to the application of an integrated CO_2-based DCV and an economizer. The study considers various occupancy profiles and USA locations. The results show the savings could be up to 20% as compared to the current operating strategy implemented in the existing system, and these savings depend mainly on actual occupancy profile and building locations. The objectives of the study include: (1) Modeling of an existing 118,000 ft^2 middle school located in North Carolina with building simulation energy software, e-Quest. (2) Model calibration by comparing the energy consumptions simulated by the model with the actual monthly energy data collected over five years, and (3) Energy savings calculations by running the validated model with CO_2-based demand-controlled ventilation DCV and economizer for different occupancy profiles and USA ASHRAE climate zones, as compared with the actual existing ventilation strategy.

CHAPTER 1

Introduction

In the present day, developed societies have a great impact on human lives. People spend most of their time indoors in facilities such as homes, schools, hospitals, and so on. In the United States, people spend 80-90% of their lifetime inside buildings (Evenson et al., 2005). Therefore, breathing fresh air inside buildings is an essential need for people. Designing indoor environments of a building should consider all what affect occupants as thermal, visual, acoustic, furniture and indoor air quality. Indoor air quality (IAQ) inside a building has a significant effect on occupants' health, performance, and productivity (McDowall, 2007).

American Society of Heating, Refrigerating and Air Conditioning Engineer (ASHRAE), specifies mechanical ventilation for commercial buildings to dilute contaminants generated from people and building materials. For example, ASHRAE 62.1-2010 indicates the acceptable indoor air quality, based on a specified amount of ventilation required for each conditioned space related to number of occupants and building type (ASHRAE, 2011). Air required for ventilation should meet the design condition of air supplied to the conditioned space. Design conditions should implement ASHRAE 62.1-2010 ventilation for acceptable indoor air quality and AHRAE 55 for thermal comfort (ASHRAE, 2013). ASHRAE 55 standards meet the thermal comfort level so people are comfortable enough while inside buildings (Taleghani et al., 2013).

Creating a comfortable healthy indoor air environment for people inside buildings requires certain amounts of ventilation based on number of occupants and building type. The fresh air provided to ventilate a building needs the following: (1) fans to force air to be entered, re-circulated, and exhausted from the building, (2) heating/cooling coils to modify the air until the design condition is met. Fan and coil energy usage impacts total energy consumption of HVAC systems (McDowall, 2007).

Electrical fans and heating/cooling units are used to introduce fresh air to ventilate a Building. Both of these methods consume energy and impact total building energy use. Extra ventilation means additional loads added to the system. Additional energy consumed by the building results in extra costs. It also influences the environment negatively by increasing CO_2 emission into the atmosphere (Pérez-Lombard et al., 2008). Although an air-conditioning system provides a healthy productive life, it consumes additional energy. The energy crisis and the greenhouse awareness have raised the flag to efficient building energy use.

Energy efficiency is strongly related to the economic growth rate and to the per capita energy use in numerous engineering applications (Long et al., 2011). Moreover, energy efficiency and energy conservation in buildings should not compromise a comfortable environment for occupants (Filippín, 2000; Markis and Paravantis, 2007; Santamouris et al., 2007; Banfi et al., 2008).

This study explores methods of improving the efficiency of heating, ventilation, and air-conditioning (HVAC) systems. Thus, the savings can be obtained while assuring IAQ and thermal comfort is reached by applying the ventilation control strategy and economizer. Subsequent sections in this chapter discuss energy and the greenhouse crisis, the impact of commercial buildings on energy use, and the impact of indoor air quality (IAQ) on human health and comfort.

1.1 Problem Statement

1.1.1 Energy Crisis. Energy is one of the most important sources in global modern civilizations, which is connected to every aspect of human life to adapt environment and human needs. Energy can be electrical, heating, lighting, mechanical, chemical, and even nuclear energy. Although the energy crisis started in the late 1970s, the continued increase in global energy demand caused a wide usage of conventional fossil fuel, which resulted in the energy crisis. Since 2007, the world market energy consumption has experienced an annual increase of 1.4%, and is predicted to increase as high as 49% by 2035. Compared to 1990, the United States has clearly reached its limit, and an obvious imbalance exists between energy production and energy consumption (Long et al., 2011). This energy crisis can be as an inclusive usage of energy with the imitate (not sure if this is the right word you were looking for) shortage of primary energy.

1.1.2 Global Warming and CO2 Emission Crisis. CO_2 emissions from fossil fuels increased by over 16 times between the years of 1900 and 2008, and by approximately 1.5 times between 1990 and 2008 (EPA, 2013). The highest level of greenhouse gas is found in developed countries (Omer, 2008). Scientific researchers predict that global warming will be greater than anyone has seen in the last 10,000 years (Long et al., 2011).

1.1.3 Building Impact on Global Energy Use. Currently, building sectors in developed countries are responsible for 40% of the primary energy use, 70% of electricity use, and 40% of greenhouse gas emission (Omer, 2008). Furthermore, energy used by buildings is one-third to one quarter of global energy consumption, and one third from global fossil fuel consumption, as half of that is consumed for HVAC systems (Taleghani, Tenpierik et al. 2013).

1.1.4 School Buildings, Energy and Indoor Air Quality. Schools are very important for society due the large number of school buildings and students attending them. The year of 2010-2011 reported over 98,800 public schools in the United States, and about 50 million students attended public elementary, secondary, and high schools for fall of 2012 (EIS 2013). Although existing standards ensure proper indoor air quality inside buildings, studies show that schools in specific, have poor indoor air quality (Kõiv, 2007; Theodosiou and Ordoumpozanis, 2008; Cartieaux et al., 2011). Furthermore, school buildings represent a significant part of total nation and global energy use. Studies conducted by the U.S. Department of Energy demonstrate that the waste in U.S. school buildings is one third of their energy use (NERI, 1990; Zeiler and Boxem, 2013). According to BIT, (2007) the average end use of energy sources in the U.S., primarily school buildings, can be classified as 19% lighting, 20% water heating, 52% HVAC and 9% other usage as in Figure 1.1.

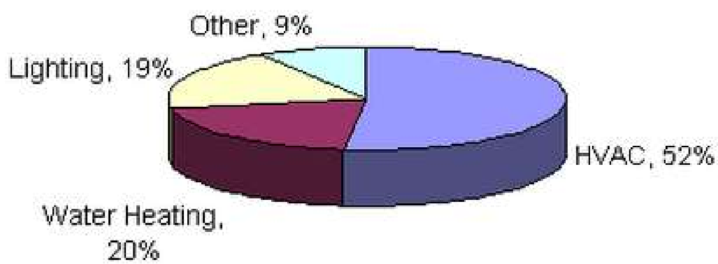


Figure 1 Average end use of energy sources in US primary school building (BIT 2007).

As evidence in Figure 1, evaluating the performance of ventilation control strategies in HVAC systems to reduce energy use is essential at this time for all the aforementioned energy issues. Furthermore, this strategy overcomes the issues of poor IAQ in school buildings. Demand Control Ventilation has been implemented in many buildings since the 1990's as a control strategy to improve the efficiency of HVAC systems. Buildings and efficient energy use with an overview of air-conditioning and HVAC systems is discussed in this chapter.

1.2 Buildings and Efficient Energy Use

Many engineering applications have employed energy efficiency concepts. These concepts are strongly related to the per capita energy use and to the economic growth rate. Energy efficiency is a measure that indicates the minimum level of energy usage for performing a task that considers technological and production processes. Recently, energy efficiency has gained more attention due to the energy crisis and greenhouse gas emission issues. Energy efficiency in buildings can be found in many fields such as in intelligent building management systems, lighting, heating, cooling, refrigerant cycle, and ventilating systems. Figure 2 shows the building's energy efficiency developments through years.

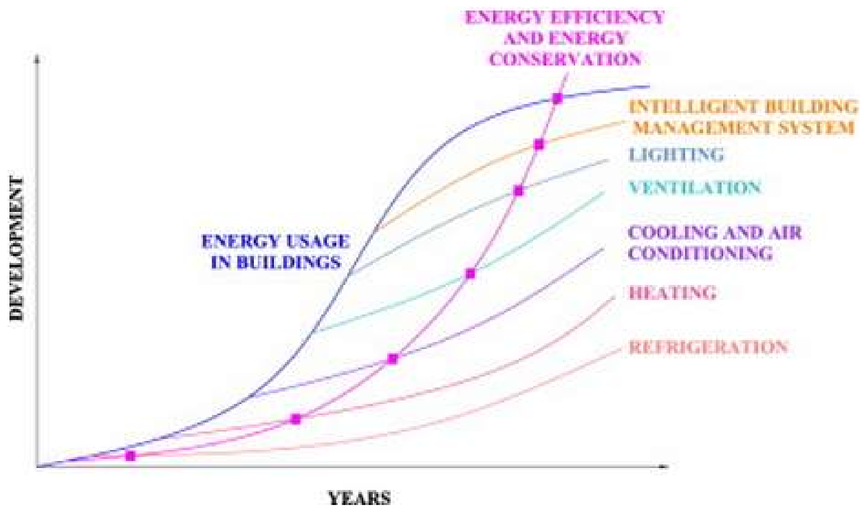


Figure 2 Energy Efficiency in Fields Related to Building Energy Use Over the Years (Omer 2008)

Heating, ventilation, and air conditioning (HVAC) systems are responsible for almost half of total energy usage in buildings. Therefore, improving HVAC system performance is essential to reduce the building's energy use; and this can be done through system design, construction, equipment efficiency, scheduling, ventilation control strategies and so on. Energy Efficiency is one of the most cost-effective means to overcome this rising in global demand of energy services while reducing emission of greenhouse gases (Long, Bull et al. 2011). Moreover, efficiency can be applicable to every field of industry with a variety of forms. In buildings field the heating ventilating and air conditioning (HVAC) as a system and its operations is highly relevant in energy efficiency applications (Escrivá 2011); operating HVAC and ventilation systems based on demand response is identified as having the highest potential in reducing energy use (Álvarez Bel, Ortega et al. 2009).

1.3 Building Air Conditioning and Ventilation Control

Since early urbanization, the use of heating, cooling, and ventilation concepts in buildings are increasingly attractive until now. With continuous technological developments, these concepts have gained attention and efforts are made to promote comfortable environments for people inside buildings. Heating, Ventilation, and Air Conditioning (HVAC) system has two objectives of providing a good thermal environment and assures proper IAQ.

The first objective is to control thermal environment by controlling temperature, humidity, and the velocity of air provided to the conditioned space. The second objective is controlling air quality. For example, ventilation specified by AHRAE 62-2010 as a (method to dilute contaminate from a conditioned space) can be used by the HVAC designers to select proper ventilation strategy to provide healthy, productive, and comfortable environment for occupants (Long et al., 2011).

Many strategies and standards are proposed and specified to improve HVAC systems performance through controlling the load in order to save energy. One of them is by controlling ventilation rate. This is particularly true due to the significant impact of ventilation on total HVAC load. Demand control ventilation with Carbon Dioxide base (CO_2-DCV) is a control strategy to adjust amount of ventilation based on real time demand to reduce energy use while assure IAQ in accordance to ASHRAE 62.1-2010 (Fisk and De Almeida 1998; Brandemuehl and Braun 1999; Wachenfeldt et al., 2007; Ng et al., 2011; Nassif, 2012). ASHRAE 62.1-2010 specify the minimum amount of ventilation required for acceptable IAQ to reduce ventilation load and energy use (ASHRAE 2011). Amount of ventilation specified by ASHRAE 62-2010 is based on building/space type and number of occupancy. Over-ventilation occur when building/space are not fully occupied which resulted in energy waste. CO_2-DCV maintain minimum ventilation rate specified by ASHRAE to eliminate over-ventilation. A significant energy saving can be obtained when implementing this strategy (Wachenfeldt et al., 2007).

Economizer operation is another method discussed later in this thesis, this operation specified by ASHRAE as a method to improve HVAC system efficiency. The concept of economizer is as simple as using outdoor cool to cool indoor building in the moderated weather, in intention to eliminate mechanical cooling and reduce refrigerant cycle and consequently energy saving can be resulted (Fisk et al., 2004; Nassif and Moujaes 2008; Nassif 2010; Yao and Wang 2010). This research discusses the impact of both CO_2-DCV and economizer for heat pumps in existing school building.

Combining CO_2-DCV strategy and economizer operation were discussed before by (Brandemuehl and Braun 1999) for typical HVAC system with single zone constant air volume; and by (Wang and Xu 2002) for type of controller used to combine both of strategies. The two strategies contributed to the improved HVAC system and enhanced energy conservation measures. They impact the overall building sustainability through:

- Ventilation control strategy by controlling ventilation intake air according to real time demand as in demand control ventilation DCV (Emmerich 1997; Fisk and De Almeida 1998; Stipe 2003; FEMP 2004; Wachenfeldt, Mysen et al. 2007; Nassif 2012)
- Efficient cooling in HVAC system is by utilizing economizer's operation, which allowing the automatic use of outdoor air cool to cool the conditioned space (Brandemuehl and Braun, 1999; Fisk et al., 2004; Hart et al., 2006; Star, 2013).

1.4 Significance of the Study

The outcomes of this study is to reduce energy use and improve building sustainability while ensure indoor air quality IAQ, by promoting the efficiency of HVAC system in commercial buildings. Two strategies are integrated for energy save (1) demand control ventilation with Carbon Dioxide base (CO_2-DCV). In this technique an attempt is done to modify intake fresh air to meet real time demand of ventilation. (2) Economizer uses the outdoor cool to cool the building during moderated weather temperatures. These two strategies significantly reduce energy consumption, system operation hours and consequently HVAC system maintenance requirements. Furthermore, CO_2-DCV and economizer operation improve indoor environment for occupants by enhancing the acceptable IAQ needed to maintain a desirable healthy productive IAQ. In addition to meet the standards and regulations of ASHRAE, the study also uses energy conservation and greenhouse awareness in school buildings, in which students will be aware of energy crises, energy conservation while ensure a proper healthy environment to strength their learning processes. Lastly, the study will serve as a future reference on the subject of modeling, validation and calibration buildings.

1.5 Thesis Statement

To overcome the crisis of energy and improve indoor air quality IAQ in school buildings, this study discusses ventilation control strategy in HVAC system to reduce energy use while assure proper IAQ. The study discusses the applications of CO_2-based demand-controlled ventilation DCV strategy integrated with the economizer operating strategy for air source heat pumps in schools. Further, the study analyzes the annual energy consumption, and determines the potential savings achieved in different locations in the USA. The study includes detailed energy analysis on an existing middle school through whole building simulation energy software.

The simulation model first is calibrated using actual monthly utility data, and then uses for saving calculations resulted from a combination of airside economizer and CO_2-DCV and with various occupancy profiles and locations.

1.6 Objectives

The main objective of this study is to introduce cost effective strategy to improve energy conservation of an existing school building served by forty-nine heat pumps. The strategy integrates the CO_2-based demand control ventilation and economizer. A simulation energy model is created to analyze the performance of these two integrated applications on energy use and the impact of different climate weather on energy use for system with the proposed strategy. To achieve our goal, the following tasks were carried out:

- Site visit: Visits are made to an existing middle school located near Boone NC to evaluate the existing system by conducting energy audit and recognize building shell characteristics.
- Data collection: Collecting energy data from the school, the monthly energy data is collected for five years. These data are used to calibrate the model for accuracy.
- Building Modeling: The school is modeled using a whole building simulation energy software (e-Quest). Detailed information about the school is entered to the software, these information's are about two main parameters: (1) system information about system type, operating hour's scheduling and seasons for the system; (2) building information related to footprint, thermal zones, building shell…etc.
- Model Validation and Calibration: The simulated monthly energy use during the cooling and heating seasons is compared with the actual data and the model is tuned to reduce the error between the simulated and actual data.

- Strategy development: Equations to predict zone CO_2 concentration is derived to determine the required amount of ventilation for a conditioned space. Amount of ventilation required for a conditioned space is varying based on occupancy profile.
- Energy analysis and saving calculations: The impact of CO_2-DCV and economizer on annual energy consumption is investigated using the calibrated model.

Simulation output for the calibrated model is compared with the simulation outputs for the model when updated with the proposed strategy to determine amount of saving. Savings obtained from the proposed strategy are determined for different climate zones by analyze the impact of weather on annual energy use. Eleven locations with different climate zones are tested..

1.7 Thesis Organization

This thesis consists of six chapters to analyze the energy use for air source heat pump when upgraded with the proposed strategy. Chapter two is literature review discussing the mechanical ventilation in HVAC system, CO_2-DCV and economizer operation. Chapter 3 describes: (1) steps for establishing *Baseline* in the simulation model (2) validate the model by calibrate it with actual utility data and (3) adjust the calibrated Baseline model to comply with ventilation requirements of new ASHRAE standards. Chapter four discusses: (1) development of CO_2-DCV through drive equations to calculate zone ventilation in single and multi zone HVAC system and (2) upgrade *Baseline* with the proposed strategy. Chapter five analyzes annual energy consumption for Greensboro city and for 10 other locations. Chapter six shows conclusion and future work.

CHAPTER 2

Literature Review

Air-conditioning of indoor environment has a significant impact on the quality of life. It ranked the tenth in engineering achievements list on National Academy of Engineers. In the United States, people spend 80-90 percent of their life time inside buildings (Evenson et al., 2005), thermal comfort and indoor air quality IAQ for the occupants inside buildings has big influence on the health and productivity of human (Ronald H. Howell 2005)**.**

Ventilating the building with a fresh air to maintain a proper indoor air quality (IAQ) is one of the major loads added to the HVAC system, it could reach up to 30% of annual heating and cooling cost in office buildings (Chao and Hu 2004; Shan, Sun et al. 2012). Ventilation is the common approach to dilute human and building contaminants, to maintain adequate indoor air quality by introduction of fresh outdoor air to the building through HVAC system.

To clearly explain the concept of demand control ventilation and economizer in heat pumps, an overview for a HVAC system and heat pump along with the mechanism of mechanical ventilation are discussed next.

2.1 HVAC System

Heating, Ventilating, and Air Conditioning (HVAC) system is a technology that provides thermal control in buildings; ASHRAE standards defines it as a system with four objectives that can control temperature, humidity, air circulation, and air quality. Properly designed and maintained HVAC system can provide comfortable indoor environment year round, which considers a key for a successful buildings performance.

A typical HVAC system consists of heating/cooling system (chiller, refrigerant, boiler, etc.) an air handling unit (AHU), distribution system with supply, return, and exhaust air system as well as humidifier. Air filters, fans, and controllers that ensure the system functions are desired. In commercial buildings, HVAC systems can be classified as central, packaged, split or individual air conditioning units. Central system cooling is generated in the chiller, distributed to the air-handling units (AHU). While heating in central systems is generated in the boiler, and distributed to the hot water system. Heat pumps, packaged systems, rooftop units, and split systems utilize refrigerant cycle that can be reversed to provide either heating or cooling mode at a time. When system in the cooling mode, heat absorbed from indoor and transfer it to outdoor through refrigerant cycle, while in the hearting mode, the cycle reversed to heat the space.

2.1.1 Heat Pump Cycle. Heat pump is type of HVAC system that employ refrigerant cycle. In a refrigerant cycle, heat moves from one ambient with low temperature to another ambient with high temperature to heat or cool the building/space. An outdoor ambient can be air, water or the ground, while the indoor ambient is the air inside the building. A heat pump can be air source, water source or geothermal according to its associated ambient. This study considers the first type (air source heat pump).

Heat pump refrigeration system consists of compressor, evaporator, expansion valve, and refrigerant in two cooper coils for the indoor and outdoor ambient, it transfers heat in and out. Figure 3 shows a diagram of basic heat pump cycles for heating and cooling cycle. When a building is in heating mode, the liquid refrigerant on the outside coils extracts heat from the air that evaporates into gas; whereas, the indoor coils release heat from the refrigerant that is condensed back into a liquid. During cooling, the expansion valve can change the direction of the refrigerant (NREL, 2001).

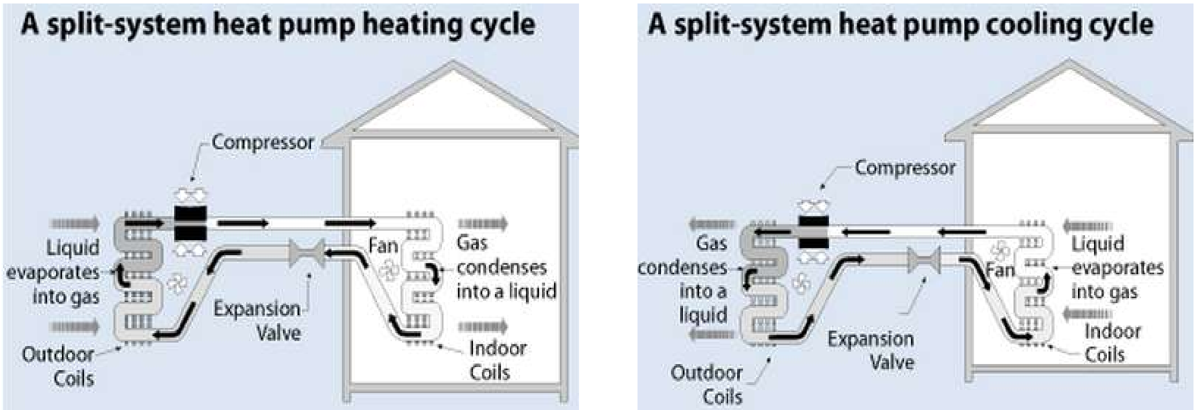


Figure 3 Basic heat pump cycles for heating and cooling methods (NREL, 2001)

2.1.2 Mechanism of Mechanical Ventilation. Ventilating the building with fresh air to maintain proper (IAQ) is one of the major loads added to the HVAC system. In some cases of the office buildings the cost of ventilation could reach 30% of the annual heating and cooling cost (Chao and Hu, 2004; Shan et al., 2012). Ventilation allows fresh outdoor air to enter the building to dilute human and building contaminants in order to ensure indoor air quality. Mechanical ventilation starts when fresh air enter building through outdoor dampers and mixes in specific portion with air from return duct. The mixture transferred through coils until it meets the design condition. Transferred air are supplied to the conditioned space through supply ducts, while return duct exhaust the extra air to outdoor through outdoor dampers and/or return it to the building through return air dampers in specific portion based on design condition. The return air is mixed with the fresh air again to start over. Figure 4 shows the ventilation process of outdoor and return air dampers for typical multi zone HVAC system (American Society of Heating 2009).

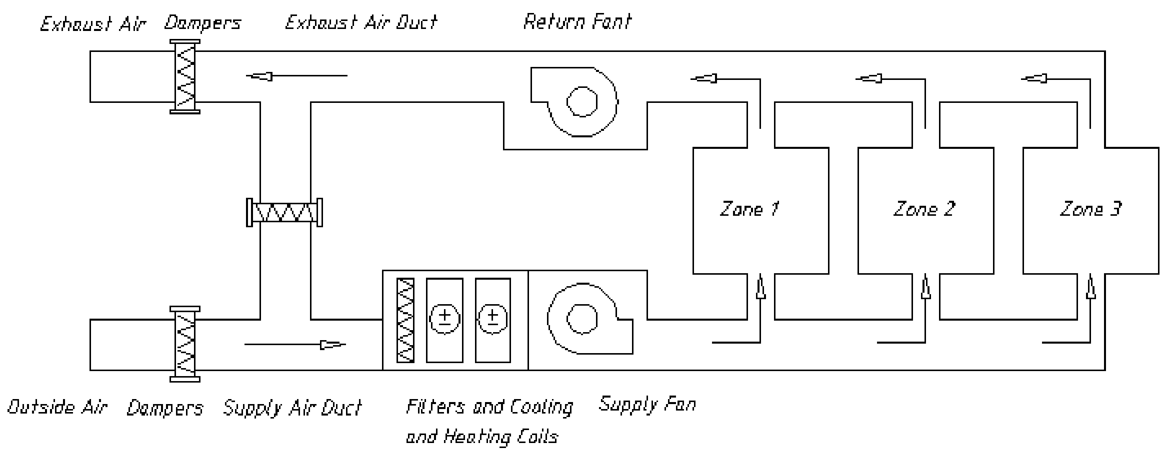


Figure 4 Typical Ventilation process with air circulation for multi zones HVAC system

Design condition of air the provided by HVAC system to the conditioned space are determined by the HVAC designer using ASHRAE 62.1-2010 (ventilation for acceptable indoor air quality) and (ASHRAE 55 for thermal comfort), and considering the following:

- Property of the mixed air; the ratio of the fresh air (from outdoor dampers) to return air (from return duct) should meet the required specifications. This can be done by determining the amount of ventilation needed for a given occupancy number and activity type in the conditioned space (Brandemuehl and Braun 1999).
- Temperature, humidity and velocity of the supply air are determined according to thermal comfort specification ASHRAE 55 with energy cost considerations (Taleghani, Tenpierik et al. 2013).

2.1.3 Ventilation Control Strategies. Ventilation has a major impact on a building's IAQ, comfort, and energy use. In the developed countries, the estimated energy due to ventilation of commercial buildings represents about 40% of the total primary energy use (Pérez-Lombard et al., 2008). Several technique have been implemented to reduce ventilation load some of these techniques are discussed below:

- Dedicated Outdoor Air System (DOAS): it provides pre-condition for the outdoor air needed for ventilating the building/space. The pre-conditioned air supplied to HVAC system mixed with the returned air and transferred based on design condition. The purpose of DOAS is to address the significant load of outdoor air required for ventilation in climate zones with high humidity or significantly low or high temperature.
- Displacement Ventilation (DV): reduces energy use by supplying significantly warmer temperature (during cooling mode) to the conditioned space. The idea is to account for the stratification of the air in the zone, by using supply air at lower level than conventional overhead supply diffusers (Wachenfeldt, Mysen et al. 2007).
- Demand Control Ventilation with Carbon Dioxide bas (CO_2-DCV): is the ventilation strategy discussed in details below.

2.2 Demand Control Ventilation

Demand Control Ventilation DCV is a ventilation rate control strategy used to address the space. Unnecessary energy use resulted from partially occupied space. When a space is ventilated at the constant rate rather than ventilation rate of real-time occupancy demand (Fisk and De Almeida 1998; ASHRAE 2011; Nassif 2012; Nassif and Al Raees, 2013). Although the main reason of ventilating building is to dilute building and occupant’s contaminants;one should consider that, contaminants generated by occupants and their activities at the early of day did not yet have reached the threshold levels due to transient nature of contaminant generation. Thus, credit of this transient can delay the design ventilation rate start up (Persily, Braun et al. 2003). Several approaches have been proposed to predict real-time occupancy number to determine ventilation rate as demand rather than the fixed design occupancy rate. These approaches include occupancy sensors, time based scheduling when occupancy profile are predictable and carbon dioxide CO_2 sensing (Persily, Braun et al. 2003).

Controlling ventilation intake rates using CO_2 base DCV CO_2-DCV offers the possibility of reducing energy use while still ensuring proper levels of outdoor air ventilation by avoiding over-ventilation when building not fully occupied. In addition, CO_2- DCV consider building infiltration as a credit for mechanical ventilation which can be significant in building ventilation (Persily, Braun et al. 2003). Many studies have shown the potential energy savings of CO_2-DCV in several case studies of commercial buildings and/or through energy software simulations. Other studies discussed the effect of climate, HVAC system type, control approach, and occupancy profile on energy save with CO_2-DCV (Brandemuehl and Braun, 1999; Nassif, 2012; Nassif, 2014). An adequate design of the CO_2 DCV should consider these issues:

- Type of control algorithm should meet the requirements of the total system.
- CO_2 sensors location, maintenance and calibration should be considered.
- Determine the amount of minimum ventilation required to control building material contaminant, which not related to occupant's contaminant.

2.2.1 Mechanism of Demand Control Ventilation. Demand control ventilation is control strategy to modify ventilation rate according to real-time demand of ventilation that is based on number of occupants. Typically, outdoor dampers are set to maintain constant ventilation rate specified by ASHRAE (Fisk and De Almeida 1998; Nassif 2012). CO_2-DCV is a combination of hardware, software and control strategy integrated to the HVAC system's main controller. The hardware is the sensors to monitor the pollution level or occupants, controller to be connected with main HVAC system controller and actuators to control outdoor air dampers (Stipe, 2003). To modify HVAC system with DCV strategy, sensors, controller and actuator to modulate damper, are all what needed. Figure 5 shows the dampers with fixed amount of ventilation and the modulated dampers.

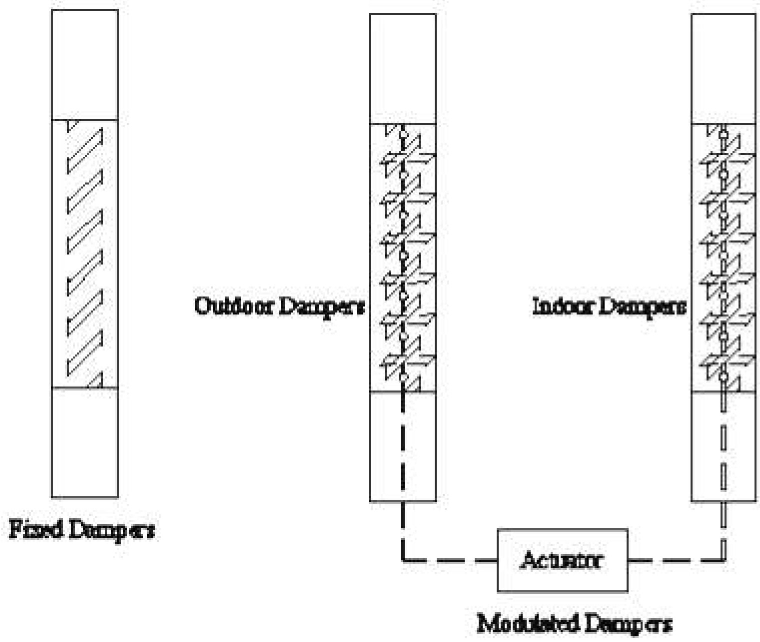


Figure 5 Fixed and modulated intake air dampers

Although, DCV strategy had been used over 20 years, the recent advance in sensors technology improve this strategy and make it one of the most feasible and cost effective strategies in this field (Stipe 2003). ASHRAE guidelines indicated that DCV strategy is recommended if properly designed and maintained.

2.2.2 CO_2 Concentration and CO_2-DCV. The quantified principals of human physiology are the basis of using CO_2 concentration for controlling ventilation in buildings. All human's exhale predictable rate of CO_2 based on occupant age and activity type (Schell and Inthout 2001). Thus, CO_2 concentration can be good indicator for number of occupants in a building, (assuming outdoor is constant concentration of CO_2. Urban areas are with constant CO_2). For example, may contain concentration ranges between 375-450 particles per million (ppm) (Schell and Inthout 2001).

Occupational Safety and Health Administration (OSHA) established that human are affected by high concentration of CO_2.; deepened breathing may occur when CO_2 concentrations is more than 20,000 ppm, while, increases respiration happen with 40,000 ppm exposure. Up to 250,000 ppm CO_2, (25% concentration of air content) exposure may cause death can cause (OSHA 2012).

However, CO_2 concentration in buildings is found normally at a level of 400 to 2000ppm, this level is not harmful to occupants (Schell and Inthout, 2001). However, many researchers found that high concentration of CO_2, can significantly affect the performance of occupants inside buildings (Santamouris, Synnefa et al. 2008; Nassif 2012; Satish, Mendell et al. 2012). In fact, the Occupational Safety and Health Administration (OSHA) established the 15 minutes threshold limit value is 30,000 ppm and for industrial environments, *the eight hours* exposure limit to CO_2 is 5,000 ppm (OSHA 2012). Figure 6 shows CO_2 levels with ventilation rate. CO_2-DCV Strategy is a combination of two technologies: CO_2 sensors to monitor CO_2 levels of the air of a conditioned space then send signals to controller, while actuator uses data from controller to adjust intake opening of dampers to meet ventilation rate required (FEMP 2004).

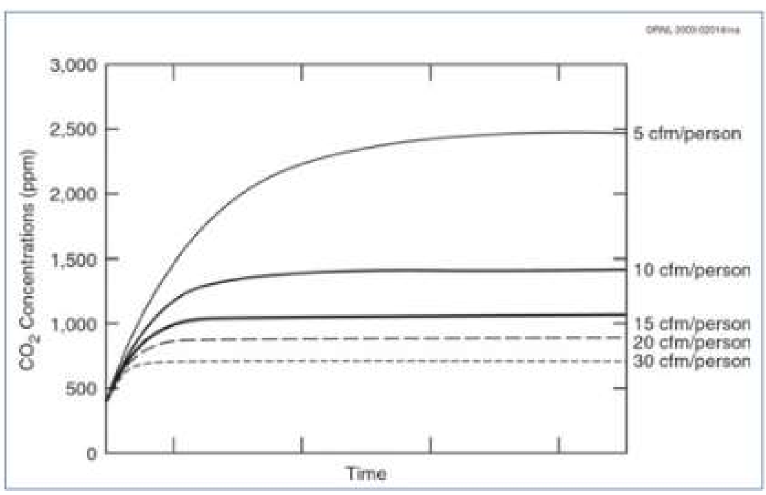


Figure 6 CO_2 level and ventilation rate in typical office building activity (FEMP 2004)

2.2.3 CO_2 Sensors. Sensor technology designed to measure gases. It uses physical or chemical interaction between the sensor and the target gas to be measured. This process causes the sensors to be degraded in readings. Degradation in readings requires frequent replacement or calibration.CO_2 is one of inert gasses, which illuminate the use of any conventional interactive technology. CO_2 Sensors technology uses the concept generated from the fact that different gases absorbed different infrared energy at specific and unique wavelengths in the infrared spectrum, is used in CO_2 sensors technology. Therefore, the most common technology commercially available for CO_2 sensors is using some form of infrared-based detection. Now a day, CO_2 sensors in HVAC applications utilize two technologies that use infrared measurement of gases. These two types of CO_2 technology have potential for low cost but have different operational characteristics. All types of sensors need to be frequently calibrated for reliable readings (Schell and Inthout 2001).The calibration can be outdoor when the CO_2 concentration is known and constant. Figure 7 shows a wall mounted CO_2 sensor.

Figure 7 CO_2 Sensor wall mounted (CO_2 meter.com)

2.2.4 Sensor's Location. Sensors are typically placed in the building/space that needs to be controlled, Sensors should be mounted at height of 3-6 ft form the floor level, and not to be close to direct people breathing (Fisk, 2010). They might be mounted in the wall as a thermostat CO_2 concentration for the inner space, or in the return air ducts.

Readings from sensors are collected then fed to HVAC system main controller, or different controller to adjust the intake fresh air dampers and adjusted the amount of ventilation by actuator according to real-time occupants number. Figure 8 is a schematic of single zone HVAC system upgraded with CO_2-based DCV.

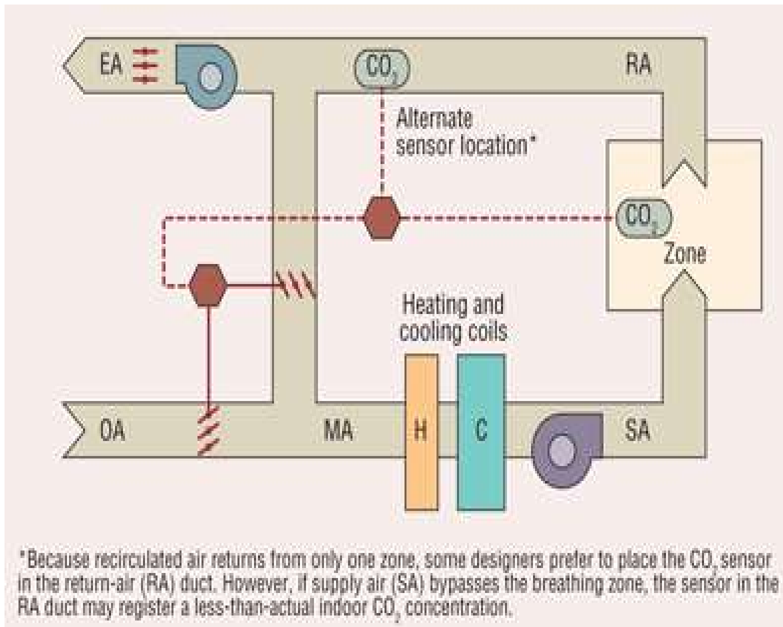


Figure 8 CO_2-DCV used in a single-zone HVAC system (Murphy and Bradley 2008)

2.2.5 Buildings Recommended with DCV. Demand Control Ventilation should be implemented where saving in energy is essential. Examples of such applications include:

- Buildings with high utility rate or crises of peak energy load.
- An predictable occupancy profile.
- Buildings with large spaces such as: assembly rooms, auditoriums, and lecture halls, large retail buildings, shopping malls, movie theaters, restaurants, bars, banks, outpatient areas in hospital, and hotel atriums or lobbies.
- Buildings with great impact of Heating and/or cooling on the HVAC system and energy cost due to sever climate weather.

2.2.6 CO2-DCV Advantages: The use of CO_2-DCV reduces the energy use by avoiding over ventilation when the conditioned space is not fully occupied. Advantages of CO_2-DCV include:

- Efficient energy use for HVAC system upgraded with CO_2-DCV.
- Maintain acceptable indoor air quality, and meet ASHRAE Standards and ventilation regulations.
- Achieve LEED rating points.
- Eliminate operation hours of major equipment in HVAC system.
- Improve humidity control in climates where the humidity is dominated; by eliminate the unnecessary humid outdoor air to inter building.

2.2.7 Impact of CO2-DCV. With the advances in CO_2 sensors technology maintenance is not problem anymore. Advanced sensors have self automatic recalibration (FEMP 2004). However, frequent calibration is recommended. This can be done by matching sensor readings during the period when the building is unoccupied with constant outdoor air readings. Advanced sensors can sense calibration problems and alert maintenance about the problem.

2.2.8 Saving with CO_2-DCV. It is reported that (FEMP 2004) the annual energy save of the CO_2- DCV system could be in the range of $0.05 to more than $1 per square foot. Payback can be the highest in buildings with variable and unpredictable occupancy profile and with high-density spaces (e.g., auditoriums, school buildings, conference rooms, and retail buildings). Other high expected payback of CO_2-DCV may be found an areas of high utility rates, and in locations with sever climate where high heating/cooling demand (FEMP 2004).

2.2.9 Cost and Pay Back from CO_2-DCV Strategy. Over the last several years, sensors cost dropped to about half of the price. Now a day, the cost of the uninstalled CO_2 sensors is ranging from $250 to $260 each. Installation cost for new system is $600-$700 per thermal zone served by HVAC system, while installation cost of the retrofitting varies with the system type (FEMP 2004). The cost to retrofit the controller for systems with an existing direct digital controller DDC programmable controller is from $700 to $900 per thermal zone. Some researcher estimated the payback period for DCV to be in the range of 3-4 years, simply by dividing System Cost / monthly energy saving (Fisk and De Almeida 1998; FEMP 2004).

2.3 Economizer Operation

Cooling in commercial buildings is required yearlong in order to control the internal heat resulted from occupants and building's equipments. During the summer season and even winter, mechanical cooling is used in commercial buildings to control internal heat gain, even when outdoor conditions are sufficiently cold enough to cool the building. Economizer with air or water source can provide "free-cooling" for buildings in moderated weather, that can significantly reduce energy use by eliminating mechanical cooling (Fisk, Seppanen et al. 2005; Hart al., 2006).

Economizer operation compares the outdoor air-conditions measurements with the return air conditions or with constant thresholds to determine whether the outdoor air dampers been fully opened or been with minimum opening to provide required ventilation, when mechanical cooling is required to cool the building.

During moderated weather, free-cooling economizer is very simple way to ensure indoor air quality along with a significant cooling energy saving if properly designed, installed and maintained (Brandemuehl and Braun 1999; Fisk et al., 2005; Hart et al,. 2006; Nassif and Moujaes, 2008; Yao and Wang, 2010; Wang and Song, 2013; Al Raees and Nassif, 2013).

It should be noted that, ASHRAE standards recommend the use of free cooling economizer as an energy conservation measure for HVAC system in commercial buildings. Economizer has reported to be installed in 12% of the buildings in region west of the US (Hart et al., 2006). Economizer can be a smart method to improve the indoor air quality IAQ with reduction in cooling electricity. Many researchers have studied free-cooling economizer as a strategy to enhance ventilation process in commercial buildings (Spitler et al., 1987; Fisk et al., 2005; Yao and Wang, 2010).

Economizer operation is proposed in this study to be integrated with demand control ventilation in air source heat pump system used in the school building. The study analyze saving in energy use for each strategy and when integrated together. Also it determines the effect of different climate weather on each.

2.3.1 Economizer Types and Features. There are two base of measurement for economizer (depend upon the use of conditioned space and the outdoor conditions).

- Dry bulb measure base: is simple, inexpensive type, easy installation and maintenance. Dry bulb measure base mode use a standard thermometer to measure the dry bulb temperature without humidity consideration, thus recommended for dry weather condition.
- Enthalpy measurement base mode or wet bulb temperature: this type measures the energy content of air. It is a refinement of the dry bulb, by providing high level of comfort with much of energy saving (Spitler, Hittle et al. 1987; Brandemuehl and Braun 1999). It is worth mentioning that all types of economizer have same features that address the building with free cooling mode. These features are:
    - HVAC system dampers such as in outdoor and return air dampers.

- Sensors can be mono or dual for (dry bulb temperature, wet bulb temperature)
- Actuators to control the dampers to any position of opening.
- Controller to be integrated with the main HVAC system controller.

All of the above features work together to control the outdoor air inside the building to reduce or eliminate the run of the compressor and the condenser of mechanical cooling unit to achieve saving in energy use. Economizer can also work with the compressor to improve the system by drawing the outside cooler and remove inside worm through the in/out air circulation.

2.3.2 Economizer Mechanism. During moderated weather, the outdoor sensors send a signal to turn off the mechanical cooling while fully open the outside air damper to draw the system with the fresh air. The opposite would happen when the sensors detect unsuitable weather. Algorithm control is one of the important components that achieve the proper switchover and address the building with economizer mode. Algorithm control has been the topic of discussion by many researcher (Nassif and Moujaes, 2008; Nassif, 2010). Figure 9 shows HVAC system equipped with economizer features.

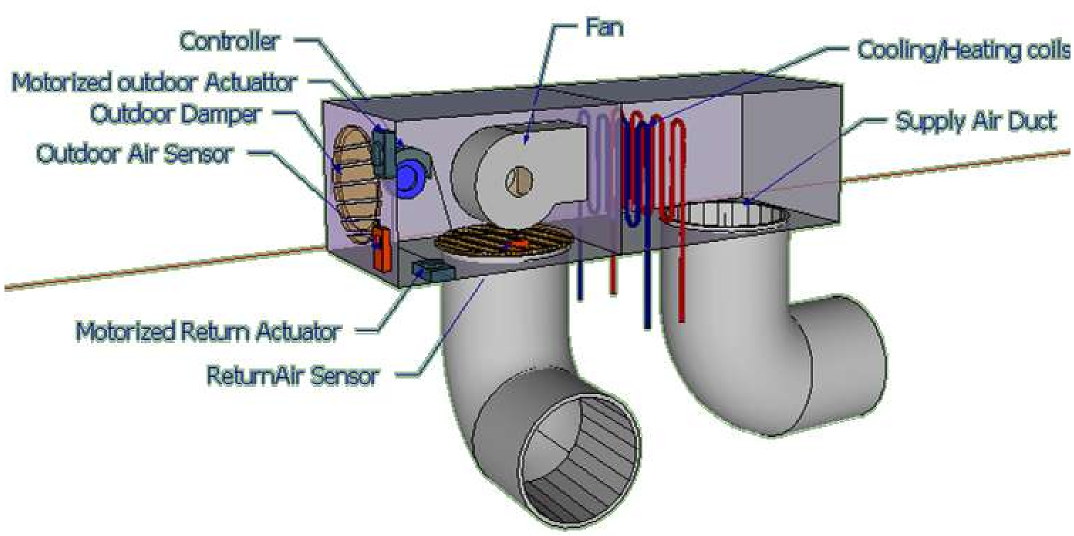


Figure 9 HVAC System equipped with Economizer features

During the moderated weather, free cooling economizer increase ventilation rate while illuminate the mechanical cooling, which can achieve reduction in energy consumption. The saving occurs if properly switchover to the economizer mode, with a two base of dry bulb and wet bulb (enthalpy) measurements through the specific outdoor and return air sensors.

2.3.3 Economizer Strategies. There are four switchover strategies that the building can switch to in the economizer mode and they depends on outside and conditioned space's use. One of these strategies is used at a time:

- "Mono-dry bulb-measure" uses an outside temperature sensor to control switchover. If the system model set as typical 55-Fahrenheit Degrees, then it would use as a threshold, below that the HVAC system uses fully outside air for cooling, above that, HVAC system uses mechanical cooling. This strategy has no consideration for humidity, which makes it better suited for areas that have low outdoor humidity.

- "Mono-enthalpy-measure" same principle of dry bulb base, but uses the humidity in consideration by measuring the energy content of air instead of temperature of air. The threshold in this case is return air enthalpy, if the outside enthalpy below that, the system

- "Dual-dry bulb-measure" uses two temperature sensors, sensor for the outside air and sensor in the return duct of HVAC. This strategy compare the two readings of outside and return duct, the less reading is use to open the damper. The outside air damper is open and return damper close, if the outside sensor reading is less than return duct reading. In this case outside air is used to cool the building. When return duct reading is less than outside air, the outside damper is close to provide minimum required ventilation, while the return damper is fully open. As mentioned in the “Mono-dry bulb-measure”, this type has no humidity consideration.

- “Dual-Enthalpy-measure” is similar to dual dry bulb base, has two sensors, outdoor and in the return duct of HVAC. In this type, if the outside air criteria are better than criteria of return duct air, the outdoor damper fully opened. Since this type has humidity consideration, the indoor air quality is improved, which makes it sufficient for IAQ and energy consumption.

2.3.4 Saving and Consideration. Economizer can reduce electricity consumption when illuminate compressor’s operating hours. The saving varies with the building type and with the weather. Most saving observed in data centers due to the high cooling requirements all around the year. Intel IT estimates that a 500kW facility will save $144,000 annually and that a 10MW facility saves $2.87 million annually when use the economizer to cool the servers with fully outdoor air. Also, they found that there is no significant difference between failure rates using outdoor air and an HVAC system. The San Jose data center in California found that using economizer may reduce cooling costs by 60% (Star 2013).

PG&E' data center experience air-side economizer and the paybacks found to be greater than two years (Star 2013).

Economizer consideration that been noticed in buildings:

- Control systems are an important component to properly operate the economizer and its integration with the main system. They are needed to activating or deactivating the mechanical cooling in system. Frequent maintains is needed (Nassif, 2010). Proper control system in economizer operation is essential to ensure that proper amount of ventilation; temperature and humidity are introduced to the building.

- Humidity control with economizer can be an issue and compromise the saving achieved. When the outdoor air is very cool, it might be very dry and the system spend energy to humidify it before supplying. ASHRAE recommended the use of economizer type that is suitable for each climate zone. Thus, considering the climate conditions is important to determine annual free cooling hours for each climate zones.
- Building with special requirements of filtered air such as labs for data center, should consider ASHRAE standard for filtering the outdoor air.

In this study, the saving varies due to different climate zones, and found to be up to 18% of the total energy consumption of the school building. The economizer that not operate properly can save less than or even has no saving. Maintenance is important to ensure the freely movement of damper parts, actuators, sensors collaboration and the controller.

2.4 Energy Simulation Software "e-Quest-3.64"

In the last decades, many of building energy simulation software had been developed to help the designers and building owners analyze energy use in a building. Whole Building Energy Simulation Software "e-Quest" is one of the most popular and widely uses software, due to the combination of simplified input and detailed output data enhanced with graphical results. To create simulation-building model in e-Quest, one need to enter the building information to the software using schematic wizard and detailed wizard. The software has the potential to start with basic information, and then move to another level of detailed data with a various selections of building components. E-Quest is an enhancement of DOE-2 when added the following two features:

- Adding wizards to create an effective building energy model: there are two wizards, the first one is "Building Creation Wizard", which also can be divided to two mode of

Schematic Design Wizard; SDW to input general information and Detailed Data Wizard DDW to input detailed information. Building Creation Wizards go through architectural design, HVAC equipment, building footprint, lighting system, occupancy, construction materials, location and building orientation. Second wizard is Energy Efficiency Measure EEM to compare results for energy efficiency measure.

- Add graphical reports to enhance detailed results.

Simulation analyzes building parameters and finalizes the detailed output of energy consumption enhanced with tables and graphics. A comparison analysis can be made with changes or when exploring the different input parameter to improve the building energy performance.

E-Quest was selected for this study to analyze the effect of CO_2-DCV and economizer on the building energy use. The capability and potential of e-Quest helped to create simulation model with an error less than 5% compare to real building's data. Figure 10 shows the three dimensional view for the school building.

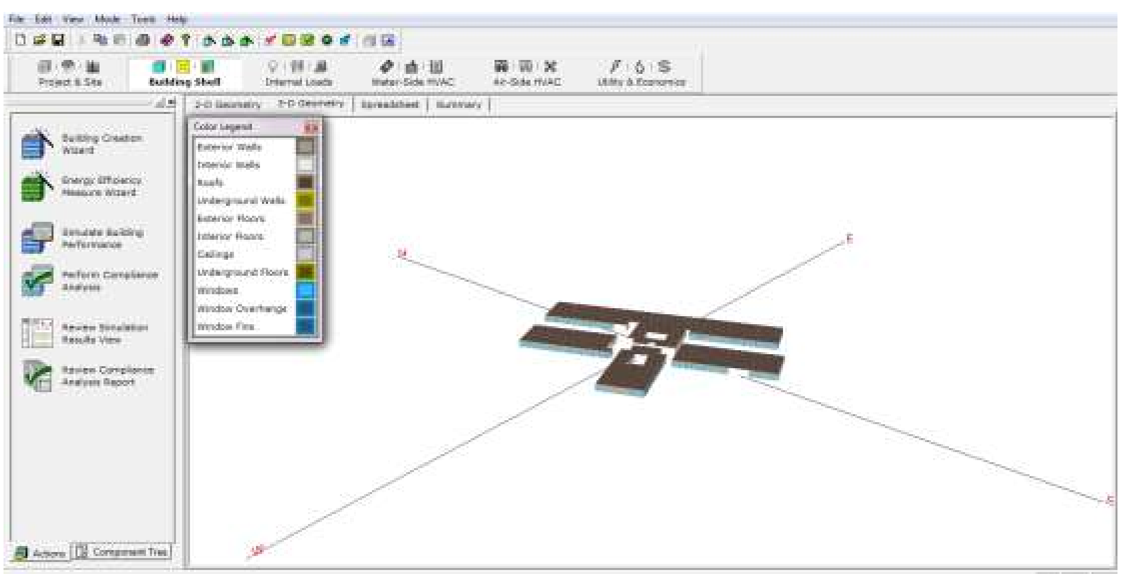


Figure 10 Three-dimensional view of the school building in e-Quest

CHAPTER 3

School Modeling and Model Validation

Introduction

This chapter covers modeling of an existing school building with the whole building energy simulation software “e-Quest”. Building’s information collected from the school is used to establish the Baseline model. The information is entered into e-Quest through several steps of modeling then validating the model by calibrates it with real utility data of school. To adhere with this calibration, the model should be updated with more of school information to reach the real data bill within 5% tolerance. Once it reaches the tolerance the model can be used as baseline. A baseline for simulation model can accurately predict the actual energy consumption of specific buildings, and use to simulate energy consumption for any modification done to the system or building shell. In our study, baseline is used as a tool to determine the annual energy use when upgrade the system by models it with the proposed strategy.

A “Modeling Plan” is important to have clear start for the process of creating reliable building model. The first step is to have plan that specifies the baseline scenario of the study. The second step is to select a simulation software for the validation, and the tolerances of validation, which is in our study decided to be within 5% of the real utility bill. Collected building data has was used to validate the model, the more data used the more reliable model will have. The data can be:

- Building’s information that include: orientation, footprints, construction materials, envelope, thermal mass, occupants, operating schedules and types of activities in the building.

- The information that are related to building systems such as: lighting system and HVAC system with zoning and operating schedule.
- Weather data for at building location is important to determine energy use for the model. The e-Quest software downloads the data via internet.

This chapter describes the school as a building simulation model and demonstrates the reasoning for choosing this type of model. A school building was chosen for the following reasons:

- Many studies have reported significant issues of poor IAQ due to high concentration of CO_2 in classrooms which exceed ASHRAE limits of 1000 ppm (Kõiv 2007)
- Energy waste in school buildings represents one third of total building energy use (NERI 1990; Zeiler and Boxem 2013).

For the above mentioned reasons, this study uses an existing public school in North Carolina to create a simulation model (in whole building energy simulation software e-Quest) to evaluate the performance of the proposed strategy for heat pump in school building. For a reliable model, the baseline is validated by calibrated it with actual utility bills of the school within 5% tolerance. The validated model can accurately predict energy consumption when any modifications done to building shell, orientation or HVAC system. Baseline of the model is discussed in chapter four when applied demand control ventilation for different occupancy profile and economize operation.

3.1 Existing School Building

The public middle school located near Greensboro North Carolina was built in 2002 to serve around 720 people. The school is in session for 9 months from 7:45 AM to 3:30 PM Monday through Friday except for holidays and school breaks. Thus it is normally occupied for fifty hours a week during the school year. The building has typical wall with brick veneer exterior and plenty of double glazed windows to allow daylight to enter the building.

3.1.1 School Footprint. A 133,200 ft^2 spanned in one floor within five wings as shown in Figure 11 One wing contains the gymnasium three include classrooms only, and the last wing contains classrooms, stage, kitchen and cafeteria. All other facilities are in the building's core with a total number of ninety-four rooms. Steam, Domestic hot water, Domestic cold water, and electricity are the only utilities supplied to the buildings. Therefore, electricity is the only type of utility used to heat and cool the air in the building.

Figure 11 West Wilkes School North Carolina, United State

3.1.2 School HVAC System Description. The school building uses two types of HVAC system: (1) Air Source Heat Pump (ASHP) and (2) DX Coils as described below:

1. There are forty-nine wall mounted air source heat pumps located in classrooms. The capacities of heat pumps vary from 2 to 4 tons, with airflow rates ranging from 800 to 1400 cfm. Most of them are three phase, while the rest are one phase heat pumps, most of

the heat pumps using 460 volts, the rest use 208 volts. Figure 12 shows a schematic of air source heat pump in classrooms.

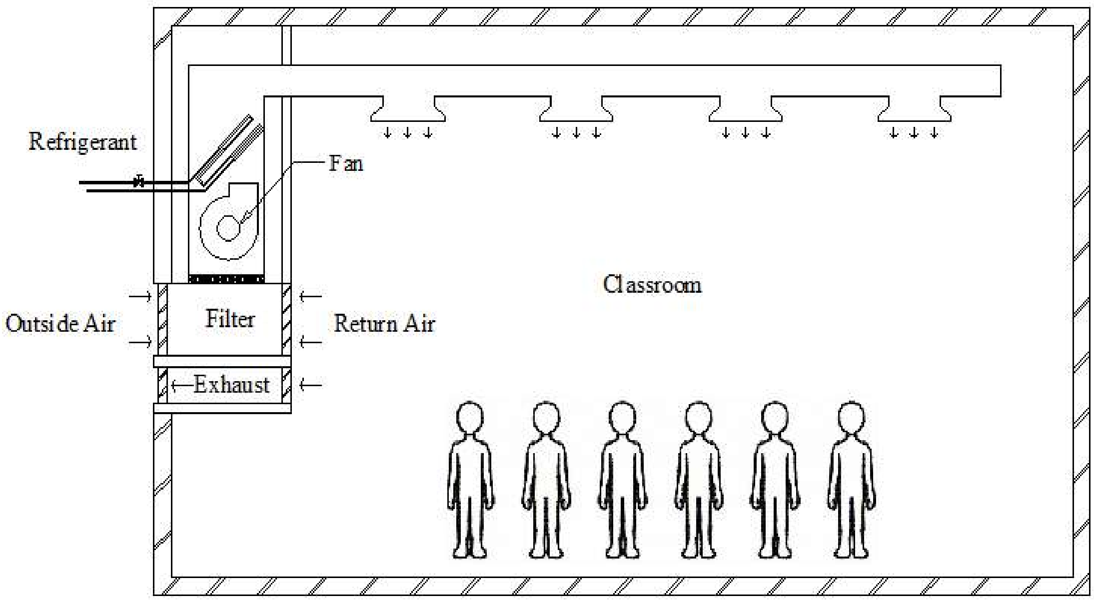


Figure 12 Schematic of heat pump for single zone in classrooms

2. There are 27 direct-expansion DX Coil Units supplying conditioned air to offices, Gyms, media center, locker rooms, cafeteria, kitchen, corridors and resource, computer art, music, dance rooms etc. The airflow rates of these units range from 600 and 8000 cfm.

The timer that controls the general areas is set to turn the system on at 6AM and off at 6PM. Each classroom has an occupancy sensor that tells the individual heat pumps to turn on and off only when the room is occupied. A fixed amount of fresh air is supplied to the space based on number of students. There is no economizer applied to this system. Thus, this study will investigate the energy benefits of using the C_{O2}-based DCV integrated with economizer operation, which can be done by installing modulated damper, C_{O2} sensor and controller. The temperature or enthalpy control strategy could be applied for economizer operation.

3.1.3 School Utility Bills. The school electricity during the 5 years period (2007-2011) were collected as shown in Figure 13. These data are used to determine the Base for school as a building model in e-Quest.

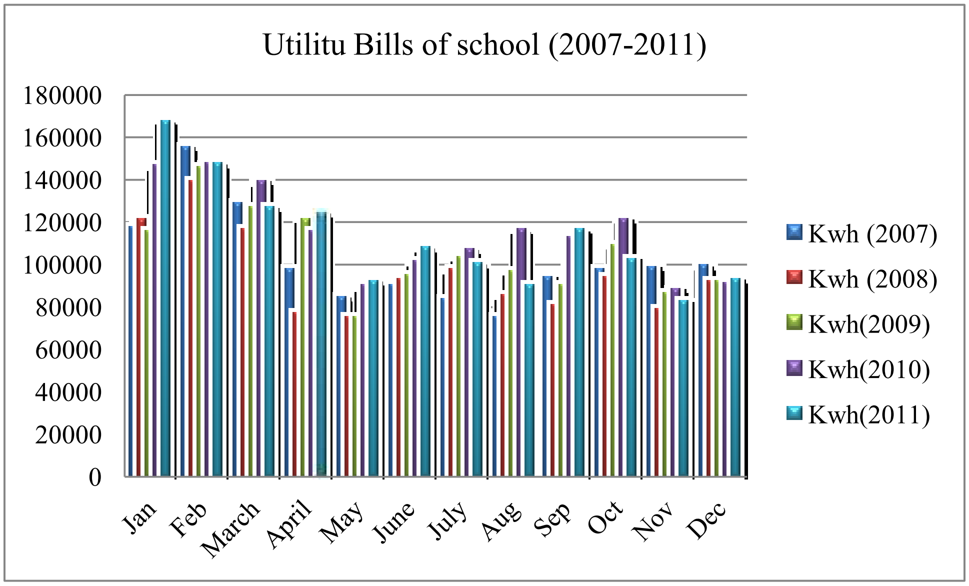


Figure 13 Actual Utility Bills of school for 5 years

3.2 Modeling School Building

Energy simulation software "e-Quest", is used to calculate the energy use for existing school building; many steps have to be taken within the software to identify the Baseline for simulation model. "Schematic Design Wizard" is used to create a file that matches actual utility bills of the school to be used later as a base. The steps taken to model the buildings are described below:

1. General Information; the basic information of the school was entered into the software through SDW; LEED-NC (Appendix G) version 3.0 was selected as code analysis. Information about location, type of building, square footage, number of floor above grade and type of cooling and heating system are all input in the software as in Figure 14.

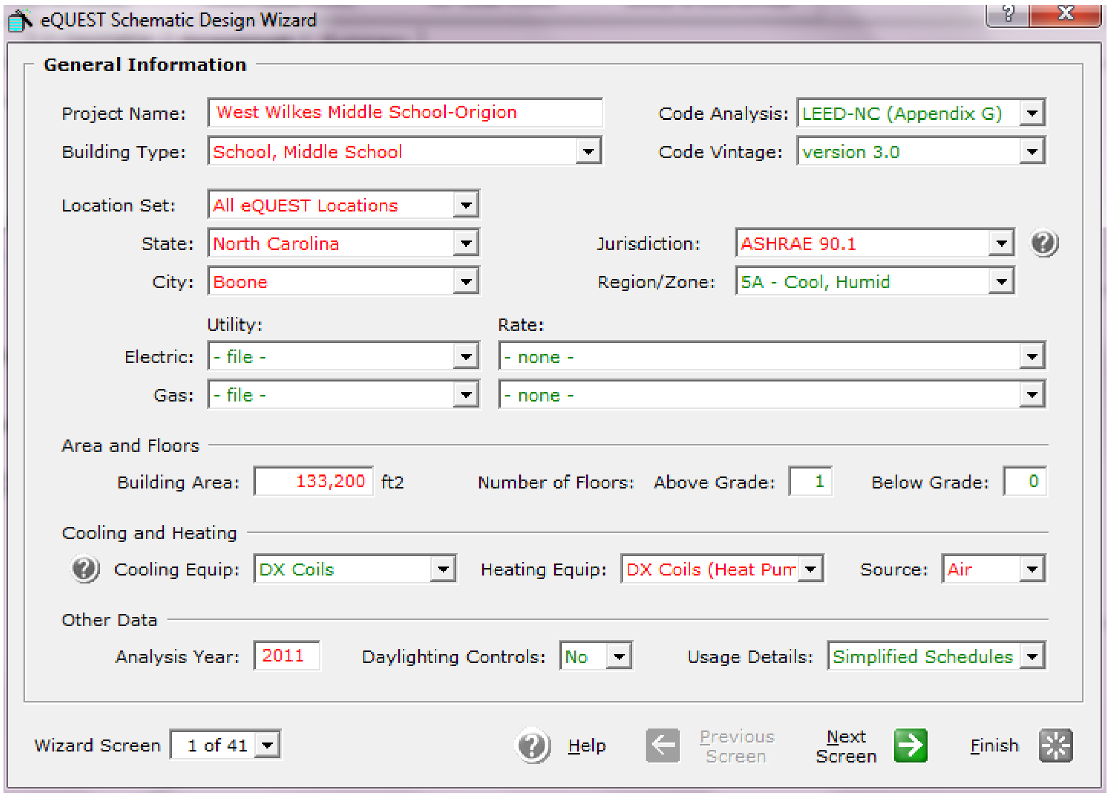


Figure 14 Schematic Design Wizard in e-Quest, basic information

2. Information from school used to create the "Building Footprint" by first identifying the "Footprint Shape" and second the "Zoning Pattern" as in Figure 15 and demonstrated below:

   - "Footprint Shape": floor plan is recreated in Auto CAD based on mechanical plans provided by the school. The Auto CAD file is imported into the software and then is used to trace the floor plan of school in e-Quest.

   - "Zoning Pattern": determine the thermal zones, which is an area within a building where an air handling unit or heat pump supplies the area with a treated air to make the space comfortable for those who occupying the space. In this school each classroom has its own zone, therefore each teacher can control the temperature in his/her classroom.

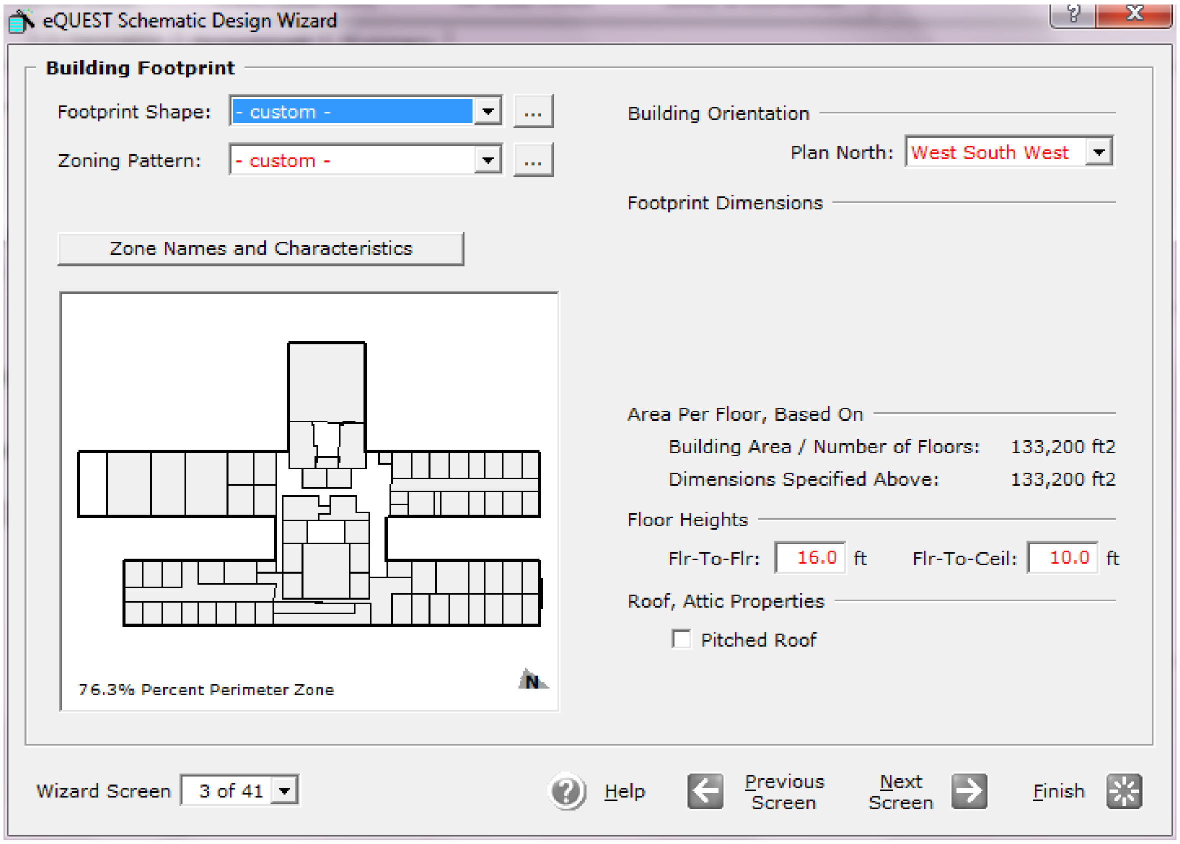


Figure 15 Building footprint through Schematic Wizard in e-Quest

3. Building Envelope Constructions to identify building shell of walls, floors, roof and input the building interior construction for inner walls. Exterior doors; types of doors and their locations were identified as part of building shell in the model. Double clear tint glass and aluminum frames windows represent 50% of walls total area. The school has no window shades nor skylight to be chosen in the software.

4. “Activity Area Allocation”: the occupied and unoccupied loads by activity area were input with all the information obtained from the school. The school uses 32-watt T8 three lamp 2X4 lights in most of the rooms in the building. Therefore, the study predicts that the watts per square foot used for lighting the building is 0.8 watts per square foot. Although lights still contribute to the utility bills T8 lights is very energy efficient.

5. Main schedule information gives the model an ability to create different seasons throughout the school year. There are multiple breaks throughout the school year that could not be added into the schedule such as spring break, thanksgiving break, and holidays. The simulation only allows two seasons to be created so the only break accounted for is summer break. Figure 16 show the scheduling in the model.

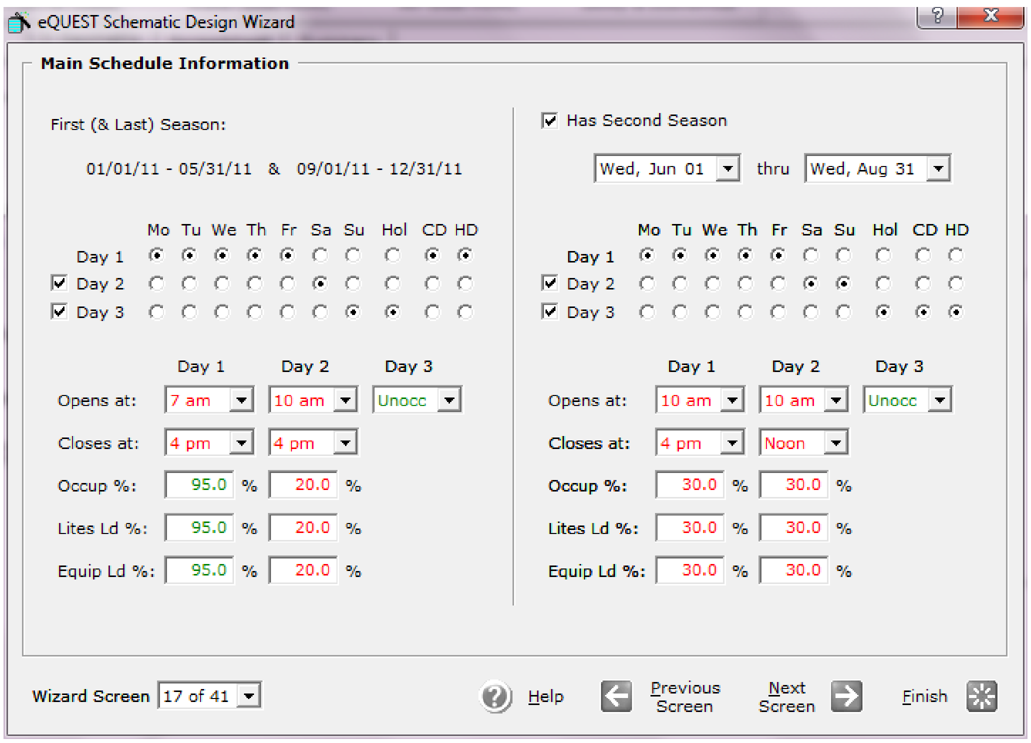


Figure 16 Scheduling in the model through Schematic Wizard in e-Quest

6. In order to control the conditions in the software, each classroom is set to a temperature of 72 degrees Fahrenheit for the summer and 75 degrees Fahrenheit in the winter.

7. Information about HVAC system: zones temperature with air flow, packaged equipments, fans with their scheduling, infiltration and heating system with ventilation and economizer information are all input of this model.

“Building Creation Wizards” through both of “Schematic Design Wizard” and “Detailed Data Wizard” are used to input the software with building information to create the baseline for simulation model. The school building is created in the software as a model. To ensure trust worthy trustworthy model that can be used as *Baseline* for this work, the model was validated to meet the actual utility data of the school.

3.3 Validating the Model

Validating the simulation model was an important step to have a reliable baseline model that can be used later to evaluate any modification done to the model. At this step, and after all of the school's information was used to create the model, simulation results provide energy use for this model. To validate the model, the output results from the simulation were calibrated for five years actual data utility bills that were collected from the school. Once the results obtained from simulations within five percent matches the data, simulation model is ready to be used as a Baseline model for future changes discussed before to improve the system.

The model outputs were compared with the five years data. Comparison shows that the model output is closer to the data of 2009 as show in Figure 17. The validation process started when, first calibrate the model using the data of year 2009, and then tested for the data of other four years (2007, 2008, 2010, and 2011). To minimize the error and to have the model within 5% from the real data more information was collected from the school and was entered to the software. Detailed information on schedule, equipment, lighting, etc. are collected and readjusted in the model. The main adjustment is related to various occupant and equipment schedules due to different days and seasons. For example, different schedules are considered for summer, winter, holiday, weekday, weekend, and so on. Our stopping criteria was to obtain an error of 5% or less. The error resulted by comparing annual consumption between the model and utility data is 0.6%. Figure 3.7 shows comparison between the simulated and utility data for five years. The model errors are 2.3% for 2007, 8.2% for 2008, 0.6% for 2009, 9% for 2010, and 6.5% for 2011.

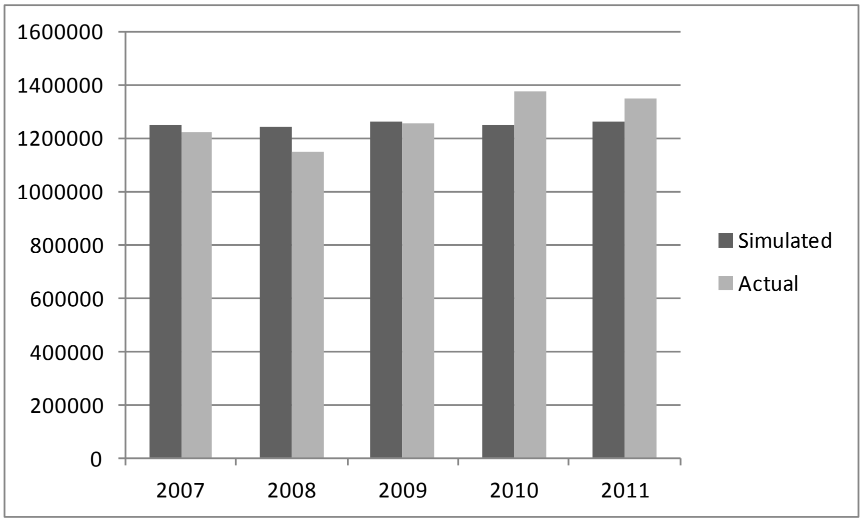


Figure 17 Comparison between the simulated and utility data for five years, in (KWh)

One technique to validate the model is by exploring an option of splitting the kilowatts used into seasons with three months in each season, for both of the model and the actual data. The seasons were split into December, January, and February for winter; March April and May for spring; June, July, and August for summer and finally September; October, and November for fall. From there the amount of the average of the three months were taken, resulted simulation to be matched within five percent of the utility bill. Figure 18 shows the comparison between the simulated and average utility data for the year of 2009

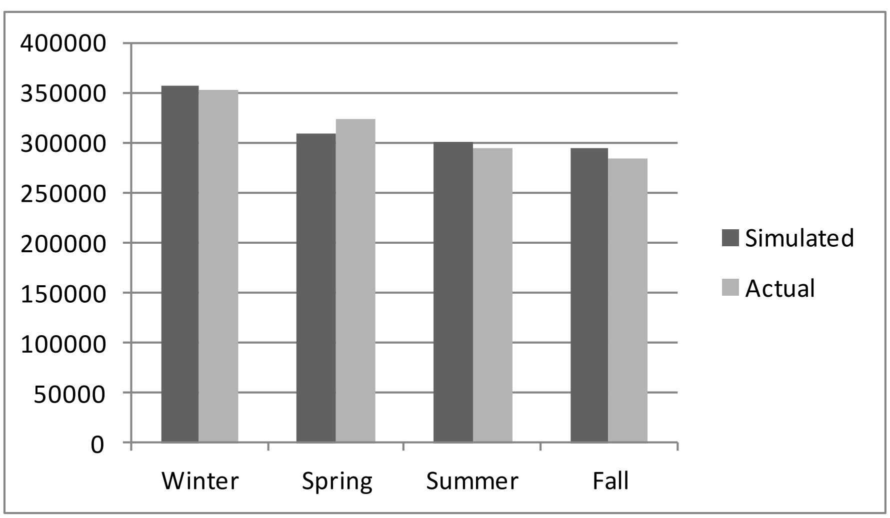


Figure 18 Comparison between simulated and utility 2009 data of the school, in (KWh)

As shown in Figure 3.8 comparing the energy consumption per season, the errors are within the 5%. For instance, 1.2% in winter, 4% in spring, 2.4% in summer, and 3.5% in fall. After the model was calibrated using the utility data of 2009, the model is then tested for the other four years (2007, 2008, 2010, and 2011). Figure 3.9 compares simulated and the average data of years 2007-2011.

Validating process for the model is stopped with the results shown in Figure 18 and 19. The school building is now represented by the simulation model, which can be used as a Baseline for further investigations.

One last step in establishing the Baseline; is by updating the model with new standard specified by ASHRAE in order to use the model later on as a base for future studies. Ventilation Strategy applied to the Baseline represents the current strategy used in the school now, which is related the old standard due to the time the school built in. The following subsection discusses the method used to adjust the baseline with the new standard.

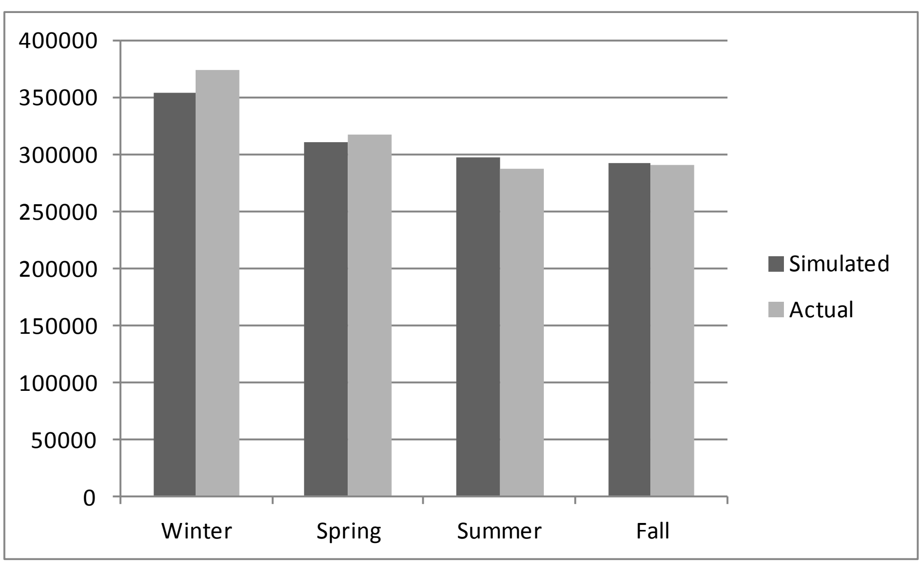


Figure 19 Simulated and average utility data of five years 2007-2011, in (KWh)

3.4 Adjust *Baseline* with New ASHRAE Standard.

Ventilation strategy used for this school is made by providing constant amount of air which is based on design occupancy regardless of occupancy profile. Outdoor air in a specific portion is mixed with return re-circulated zone air [previous ASHRAE62.1-2001]. The previous standard considers contaminants generated from people as the only source for the building contaminant. The equation used to determine minimum rate of ventilation according to that is:

$$V = R_p \times P \tag{3-1}$$

When (P) is the occupants, ventilation rates (R_p) is needed to dilute the contaminants generated by occupants according to their age and type of activity in the space, while, (P) is number of occupants and (V) represent the miinimum amount of ventilation required to the space in cubic feet per meter (cfm). On the other hand, the current ASHRAE 62.1-2010, requires minimum ventilation rate to include the building rate (R_a) where is based on type of activity in space, and V as a function of the number of zone occupants P and the zone floor area A is given by this equation:

$$V = R_p \times P + R_a \times A \tag{3-2}$$

The R_p and R_a are determined from the table in Standard 62.1-2010 user's manual, based on the type of activity in the conditioned space and age of occupants as shown in Table 1.

Baseline model was adjusted according to the new standard by applying the new equation and using the detailed data wizard as shown in Figure 20. At this step, the baseline model is ready to simulate annual building energy use for any modifications done to the HVAC system or to the building shell.

Table 1

Occupants and building rates base on ASHRAE 62.1-2010 specifications

Occupancy Categories	Occupancy Rate (R_p) cfm/person	Area Rate (R_a) cfm/sq ft	Ventilation Equation
Classroom- age 9 plus	10	0.12	10 * R_p + 0.12 * R_a
Art Classrooms	10	.18	10 * R_p + 0.12 * R_a
Computer Lab	10	0.12	10 * R_p + 0.12 * R_a
Multi-use assembly	7.5	0.06	7.5 * R_p + 0.06 * R_a
Cafeteria	7.5	0.18	7.5 * R_p + 0.18 * R_a
Corridors	-	0.06	0.06 * R_a
Office spaces/Lobby	5	0.06	5 * R_p + 0.06 *R_a
Gymnasium	-	0.3	0.3 * R_a

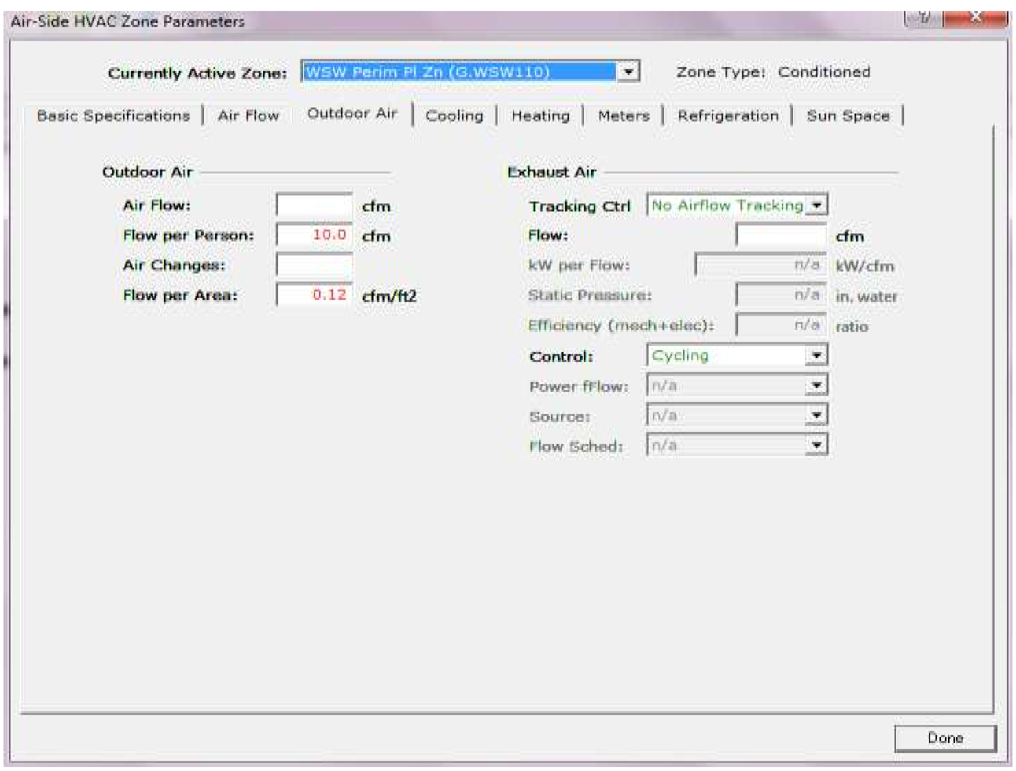


Figure 20 Amount of ventilation in the model based on the current standard

3.5 Baseline Model

Baseline output result will be used later as a threshold when the model is modified for the proposed strategy. HVAC system in the *Baseline* model can be prescribed as:

- A system with 49 packaged single zone ASHP and 27 DX coil for cooling and heating, the two systems are set to turn on and off according to a specific schedule based on school year breaks, holidays and activity.
- A model with 74 thermal zones, each classroom is a single zone served by a heat pump. Other facilities are served by DX coils as a multi zones system.
- Ducted return air system for both type of systems.
- Fans with variable speed drive.
- Design temperature is 75̊ F for the space with 55̊ F for supply air in cooling mode, and 72̊F for the space with 90̊ F for supply air in heating mode.
- In “Main schedule Information” the school has two seasons; the first season is for school year and the second season is for summer. The schedule has three different hourly schedule days: day one is for regular school days, from 7AM to 4PM with 95% occupancy profile, day two for Saturdays from 10AM to 4PM with 20% occupancy profile, day three is off, for holidays. Summer season also has three days: day one is from 10AM to 4PM with 30% occupancy; day two is from 10AM to noon with also 30% occupancy, day three is off.
- *Baseline* ventilation strategy is complying with current strategy of school by providing the space with a constant amount of outdoor air. In addition, it is complying with the new standards by the amount of outdoor air been provided to the space.

- The school uses the electricity for heating and cooling as a function of building load and location.
- Locations of the *Baseline* are selected to be Greensboro city in North Carolina. To explore the impact of different climate on CO2-DCV and economizer performance, the *Baseline* location changed to various selected places with different climate weather. There are eight ASHRAE climate zone weather for US. Eleven locations are selected among the eight climate zones for this purpose.

CHAPTER 4

Strategy Development

Introduction

In this chapter, efficient technique is proposed in this work to reduce air source heat pump (ASHP) system energy consumption by combining demand control ventilation along with economizer operation. To improve ASHP efficiency with this strategy all what need to be added are sensors, controller and actuator.

The reason why ventilation consider on of most important loads been added to the system, is that energy is used to transport the outdoor air through mechanical parts and condition until meets the design condition level. Furthermore, amount of ventilated air should comply with the new standard to ensure a proper IAQ for occupants in the building. Ventilation load and the energy consumed by that are mainly affected by the amount of ventilation provided to the space. For this reason, standard specifies maintaining a minimum amount of ventilation.

The minimum outside airflow, specified by standard, must be introduced to the building through the system, then been supplied to the space. Typically, and in the absences of CO_2-DCV, a fixed amount of fresh air is processed through the system to the space based on design occupancy even when the space is not as in design occupancy. CO_2-DCV is adjusting the intake air to match real time occupant needs for indoor air quality and control over ventilating. The airflow rate for actual occupants is below the design minimum airflow rate, when the design setting is for the full occupancy. In this case unnecessary heating/cooling load is required to condition the over ventilated air. Demand control ventilation is recognized as being a method of ensuring a building that minimizes cost of effective ventilation while maintains indoor air quality and through the same design condition.

The proposed strategy is by adding economizer to CO_2-DCV through same controller and damper actuator. Economizer control mechanical cooling by use the outside cool to cool the building instead, in which energy saving can be obtained.

The proposed strategy that integrate both strategies is discussed in two ways by this study:

1. Propose ventilation rate calculations for the one zone heat pump system used in classrooms and multi-zone for DX coils system used in offices.
2. Upgrade the calibrated model (*Baseline*) with the proposed strategy to estimate the annual energy use from simulations output result.
3. Analyze the output result from each case of the strategy, by compare it with *Baseline* output results.
4. Determine the potential saving obtained when apply the proposed strategy for different ASHRAE climate weather locations.

In the following subsection, ventilation rate calculations and model validation for CO2-DCV and economizer will be discussed.

4.1 Ventilation Rate Calculations

The existing school building has two type of system as mentioned before, first is the DX coils with multi-zone to serve offices and the other facilities in school. The second one is one-zone air source heat pump that is used to serve each classroom individually.

1. **Ventilation rate procedure calculations for multi-zone system**. The ventilation rate procedure in ASHRAE Standard 62.1-2010 has specific calculations for multi-zone systems. The Standard specifies two ventilation rates, one intended to dilute the contaminants generated by occupants (R_p) and other for building-related sources (R_a). The required minimum breathing

zone of outdoor air flow rate V_{bz} as a function of the number of zone occupants P_z and the zone floor area A_z is given:

$$V_{bz} = R_p \times P_z + R_a \times A_z \tag{4-1}$$

R_p and R_a are determined from the table in ASHRAE Standard 62.1-2010 based on the occupancy type. The breathing zone of outdoor air rate needs to be adjusted to account for the supply diffuser, and return grill locations, supply air temperature, and other factors by including the zone air distribution effectiveness E_z . V_{oz} (the required ventilation to a given space) can be represented by:

$$V_{oz} = V_{bz} / E_z \tag{4-2}$$

The outdoor air fraction in discharge air supplied to each zone Z_{dz}:

$$Z_{dz} = V_{oz} / V_{dz} \tag{4-3}$$

The outdoor air rate in all breathing zones V_{ou} (uncorrected outdoor air intake flow):

$$V_{ou} = \sum(R_p \times P_z) + \sum(R_a \times A_z) = R_p \times P_b + \sum(R_a \times A_z) \tag{4-4}$$

The total number of occupants P_b (occupants in whole building) is equal to the sum of the occupants in each zone P_z. The uncorrected outdoor air fraction X_s to the system air supply air V_{ps}

$$X_s = V_{ou} / V_{ps} \tag{4-5}$$

The efficiency for each zone E_{vz}:

$$E_{vz} = 1 + X_s - Z_{dz} \tag{4-6}$$

The system efficiency E_v

$$E_v = \min (E_{vz}) \tag{4-7}$$

The minimum required system outdoor air flow V_{ot} and corrected outdoor air fraction X_{sc}:

$$V_{ot} = V_{ou} / E_v \tag{4-8}$$

$$X_{sc} = V_{ot} / V_{ps} \tag{4-9}$$

2. **Ventilation rate procedure calculations for one-zone system.** The required fresh air based on ASHRAE Standard 62.1-2010 for one zone system is simply given by the following equation:

$$V_{oz} = (R_p \times P_z + R_a \times A_z) / E_z \tag{4-10}$$

3. **Proposed ventilation strategy.** The algorithm used for CO_2 control is based on the calculations in Appendix A of the ASHRAE 62.1-2010 user's manual (ASHRAE. 2010) and Murphy (Murphy 2005). The procedure could use (a) proportional control or (b) single zone as described by Murphy (Murphy 2005).

a. <u>Proportional control.</u>

ASHRAE Standard 62.1 provides the mass balance equation to predict the difference between indoor CO_2 concentration (C_z) and outdoor CO_2 concentration (C_o) at steady-state conditions (the air supplied to the space is assumed to be well mixed and the efficiency E_z=1):

$$V_{oz} = N_z / (C_z - C_o) \tag{4-11}$$

The N_z is the CO_2 generation rate and it is a function of people number ($N_z = C \times P_z$); where C is a constant value related to the occupancy activities, level, diet, health, and etc. The space CO_2 concentration C_z is given by (using Eq. 4-11 and $E_z = 1$):

$$C_z = C_o + N_z / V_{oz} = C_o + (C \times P_z) / (R_p \times P_z + R_a \times A_z) \tag{4-12}$$

The airflow rate supplied to the space is determined by the following proportional control equation:

$$V_{oz} = (C_{(z\text{-actual})} - C_{(z\text{-min})}) / (C_{(z\text{-design})} - C_{(z\text{-min})})\ (V_{(oz\text{-design})} - V_{(oz\text{-min})}) + V_{(oz\text{-min})} \tag{4-13}$$

The required CO_2 concentrations at the design of full occupancy ($C_{z\text{-design}}$) and at the minimum occupancy ($C_{z\text{-min}}$) and the required fresh air based on the design population $V_{oz\text{-design}}$ and on the minimum occupancy $V_{oz\text{-min}}$ are determined as a follow.

- The required CO_2 concentration at the design occupancy ($C_{z\text{-design}}$) is determined by Equation (4-12) and using $P_{\mathbf{z}}$ at design occupants ($P_{\mathbf{z}\text{-design}}$).
- The required CO_2 concentration at the minimum occupancy in space $C_{\mathbf{z}\text{-min}}$ is determined by the same equation but by using $P_{z\text{-min}}$, as 40% of design occupants (adjustable).
- The required fresh air based on design zone population $V_{\mathbf{oz}\text{-design}}$ is determined by Equation (4-10) and using P_z at the design occupancy ($P_{z\text{-design}}$).
- The required fresh air based on the minimum occupancy in space $V_{\mathbf{oz}\text{-min}}$ is determined by Equation 10 and by using minimum $P_{z\ min}$ as (40% of design occupant).

This proportional control strategy is easy to implement and yield an outdoor-air intake flow that equals or exceeds the requirements (Murphy 2005).

b. <u>Single set-point control.</u>

In a single set-point control, the modulated outdoor damper is controlled to maintain the space CO_2 concentration $C_{z\text{-set-point}}$ at a value calculated by equation (4-12) as a follow:

$$C_{(z\text{-min})} = C_o + N_z / (V_{(oz\text{-min})}) \tag{4-14}$$

If the OA damper reaches $V_{oz\text{-min}}$ and the population in the zone continues to drop, the OA damper remains at $V_{oz\text{-min}}$. This over ventilates the zone, so the indoor CO_2 concentration drifts downward. Conversely, as the current population nears design, the zone will be over ventilated.

As described by Murphy (Murphy 2005), the “single set-point” approach results in an outdoor-air intake flow that equals or exceeds the ventilation rate required by ASHRAE 62.1. It’s simple to implement; and, depending on the characteristics of the zone, it may result in less over-ventilation at partial occupancy than the "proportional control" method. It also requires a modulating outdoor air damper, but the controller needs only one OA-damper set-point ($V_{oz\text{-}min}$) and one CO_2 set-point (*Cs-min*) rather than two limits for each.

4.2 Proposed Strategy Analysis Approach

The calibrated model can predicts the space heat gains or losses based on heat transfer from external load represented by building shell, and the internal load represented by (i.e., people, lights, and equipment). Amount of energy consumed, air properties and mass balances for space and criteria of air in the distribution system are all based on space design condition. Design condition determines the amount of mixed air conditions supplied by the system from outdoor air damper and/or return air dampers. Type of ventilation strategy applied determines the ratio of return air to outdoor air). Simulation software determines space load based on the building shell features, occupancy profiles, system operating schedule, space design condition and type of standard are used in the analysis.

4.2.1 CO2 -DCV Strategy. HVAC **S**ystem with typical ventilation control strategy uses minimum ventilation flow rate specified by ASHRAE 62.1-2010. Typical ventilation strategy provides constant level of air that considers only maximum design of occupancy to determine the load of ventilation. CO2-DCV maintains minimum airflow rate of ventilation, but it is adjusted based on real-time demand of occupancy. CO2 concentration in the space is at or below a specified level of the standard. The control strategy should allow ventilation load to be adjusted when the space is not fully occupied which resulted a reduction in energy use. Ventilation in this strategy is modulated through a whole system of ventilation control (CO2 sensors, controller and actuator).

The range that ventilation can be modulated through is to be in between the high of design rate (minimum ventilation rate specified by ASHRAE) and the low base of ventilation rate designed for non-occupant. The low of ventilation rate for non-occupant is represented by the ventilation that are required to dilute contaminant generated by building related source. This is represented in ventilation equation as the area of the space (A) multiplied by area rate (R_a) specified by standards.

The previous standard specified a limit of CO_2 concentration as a 1000 ppm to meet IAQ criteria. The current standard has no limitation for indoor CO_2 concentration, and the user manual presents the CO_2 concentration in a conference space to be reach 1755 ppm with steady-state condition. This concentration is with some assumption consideration such as ambient of 400ppm for CO_2 concentration and activity level of one metabolism for occupants.

CO_2 sensors can be in the space or in the return zone duct as specified by standard or can be in the supply air as discussed by Nassif (Nassif, 2012). CO_2 sensors monitor the level of CO_2 in conditioned space and send dynamic signals to controller. Controller compares these readings with the set points specified by the standard. CO_2 sensor is recommended to be mounted in all major and critical zones rather than in return or supply air duct, because the duct sensors determine the average of all zones in multi zone system. Duct sensors are preferred for zones with same pattern of occupancy profile and type of activity. In this study, a zone sensor as an option in the software is selected, due to the single ASHP uses for each classroom in the school.

4.2.2 CO2-DCV and Economizer. This work discusses the integration of economizer operation with CO2-DCV. Through that integration, maintaining the minimum amount of ventilation through CO_2-DCV is no longer conserved with the presence of economizer. With an active economizer, the outdoor airflow can be greater than the minimum to draw the space with outdoor cold air to cool the space. For this reason, economizer is deactivating the CO_2DCV . Economizer is active whenever outdoor air conditions meet sensors set points. Two types of economizer are used; mono dry-bulb temperature sensor and mono enthalpy sensor with a switchover of 70°F and 30 Btu/lb respectively. That mean whenever the outdoor air temperature is less than 70°F, the economizer is activated for the mono dry-bulb mode. And is activated when the outdoor air enthalpy is less than 30 Btu/lb for the mono enthalpy mode. To apply economizer to the model assumptions are made:

- CO_2 contaminant is the dominated the space. Any space has a significant pollutant other than CO_2 must has its own separate ventilation .
- Outdoor CO_2 concentration level is varying throughout the year and location. CO_2 level assumed to be constant in these locations.
- CO_2 generated form people are varying based on type of activity and it is greater in adults than children are. It is assumed a constant CO_2 level for all occupants. Figures 21shows schematic of ASHP with CO_2-DCV only, and with the both in Figure 22.

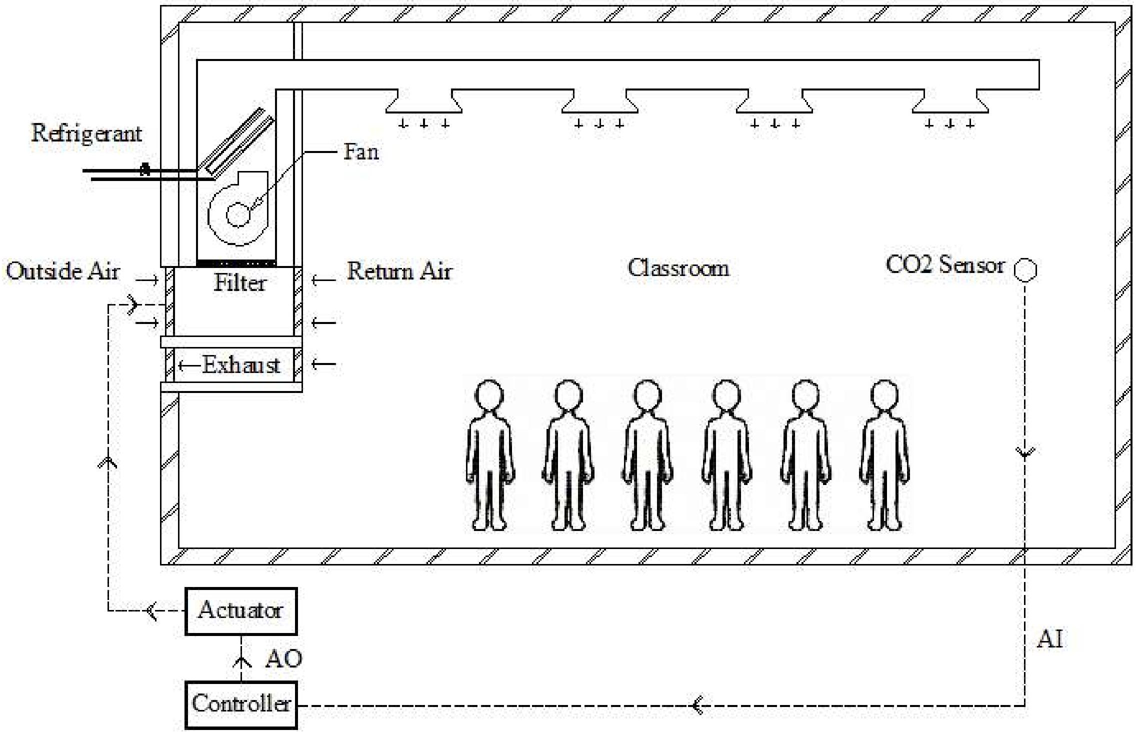


Figure 21 ASHP Single Zone System with CO_2-DCV

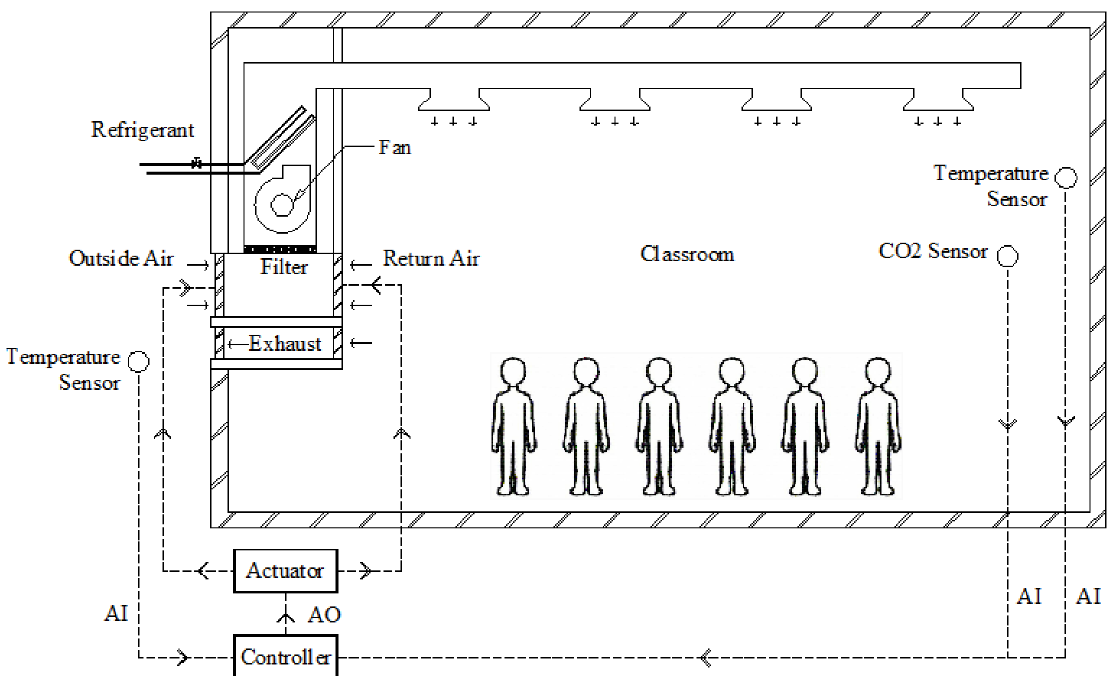


Figure 22 ASHP Single Zone System with the CO_2-DCV and economizer

4.3 Procedure to Evaluate the Proposed Strategy

The calibrated simulation model (*Baseline*) is used to analyze energy use of the proposed strategy. The software uses Typical Meteorological Years (TMY data), weather data to simulate energy use for the upgraded model and for each location. Table 2 lists the locations and cities that tested by this study.

Table 2

Locations and Climate Zones.

Climate Zone	Location/City	Indication	Weather Features
Climate zone 1	Miami Florida	1A-Miami	Very Hot Humid
Climate zone 2	Orlando Florida	2A-Orlando	Hot Humid
Climate zone 2	Houston Texas	2A-Houston	Hot Humid
Climate zone 3	Nevada Las Vegas	3B-Nevada	Worm Dry
Climate zone 4	Greensboro North Carolina	4A-Greensboro	Mixed Humid Weather
Climate zone 4	New York New York	5A-New York	Cool Humid
Climate zone 5	Lansing Michigan	5A-Michigan	Cool Humid
Climate zone 5	Denver Colorado	5B-Denver	Cool Dry
Climate zone 6	Helena Montana	6B-Helena	Cold Dry
Climate zone 7	Fargo North Dakota	7-Fargo	Very Cold
Climate zone 8	Bethel Alaska	8-Bethel	Subarctic

1. **Apply CO2-DCV to the model.** Detailed data wizard in e-Quest, has the potential to apply this strategy to the model and modify it. To apply CO2-DCV strategy to *Baseline*, all school zones in detailed data mode under “Air-Side HVAC System Parameters” and from

"Outdoor Air" are changed from "fraction of design flow" to "DCV zone sensors". To simulate the energy use under different occupancy profile, occupant's number in detailed data under "Annual Schedule" then "Day Schedules" are changed from full to various occupancy profiles. By apply the CO_2-DCV, some of model assumptions are made:

- Readings from CO+ sensors are accurate and sensors are calibrated.
- School building has infiltration of 0.5 cfm per min.
- Occupants exhale are the only source for CO_2 and building has no CO_2 removal mechanism.
- Occupants in building generate a same level of CO_2.
- Efficient HVAC Distribution system and is equal to one.

2. **Apply economizer to the model;** Economizer strategy is applied to *Baseline* through detailed data wizard, and again all the school zones in detailed data mode under "Air-Side HVAC System Parameters" and from "Outdoor Air", had been changed from "Fixed Fraction" to "OA Temperature" or to "OA Enthalpy". The free cooling economizer applied to the model with three occupancy profile, the 75 and 50% of school design occupancy in addition to full occupant mode.

3. **Testing Various Locations by E-Quest;** One of the objectives of this study is to explore the affect of different climate weather on the proposed strategy. Location of the building in the software is in the (general information) in building creation within the schematic design wizards. As the model was updated with the current standard of ventilation through the detailed data; e-Quest software does not support the information saved in detailed data when go back to schematic wizard to change the location. Thus, after changing the location in schematic wizard,

detailed data wizard can be selected to be updated with the current ventilation strategy to have the *Baseline* for a given location**.**

It is worthy to mention that one of the assumptions made when change the location, that all code requirements for a given location should be considered through the software when change the location.

The city of Greensboro was selected as first location for this work. The sequence used to change location is started before updated the current standard by: (1) change location of *Baseline,* and then apply new ASHRAE equations for the entire 74 thermal zone of the model. (2) Upgrade the *Baseline* with CO_2-DCV for all the zones with the different occupancy profiles. (3) Results for this step obtained from run simulations for each case. (4) Upgrade *Baseline* with economizer as full and with different profiles. (6) Results of this steps obtained by run simulations for each case. The sequences used in analyzing energy use for the system with the suggested strategy are shown in Figure 23.

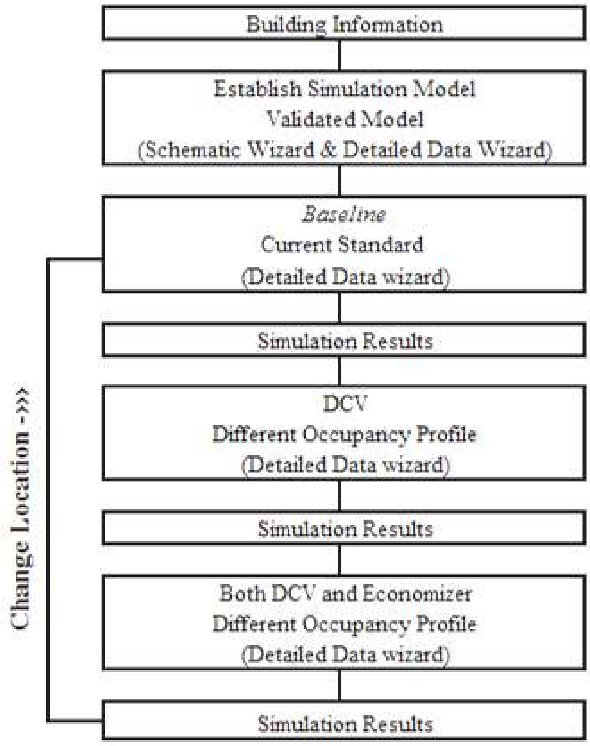


Figure 23 Steps to upgrade *Baseline* model with CO_2-DCV and economizer in e-Quest

When change the location of *Baseline,* all the 74 thermal zones in the model should be updated with the new standard equations. Then energy consumption for the new location *Baseline* can be determined by run the simulation. At this step, the strategy could be applied for the different location and run simulation in for each step as done in first location to be compared with the baseline to determine the saving.

The locations are selected from different US climate weather zones to evaluate the affect of weather on the applied strategy. The different climate zones are recognized by ASHRAE. Figure 24 shows the US map with the eight climate zones.

Eleven locations are selected to test the model, and each location has six simulations that started with the Baseline run, then with demand control ventilation different profiles and with economizer with different profiles. For the city of Greensboro more simulations are done that reach up to 20. the reason why is to have a better understanding about the relation between occupancy pattern and energy use. All results are shown in chapter 5 and visual of results for simulations in e-Quest are shown in the appendixes. For the city of Greensboro, visuals of simulation are in Appendix A1-4, while other locations are in Appendix B1-20. Output simulation run for all cities are shown in a table in Appendix C.

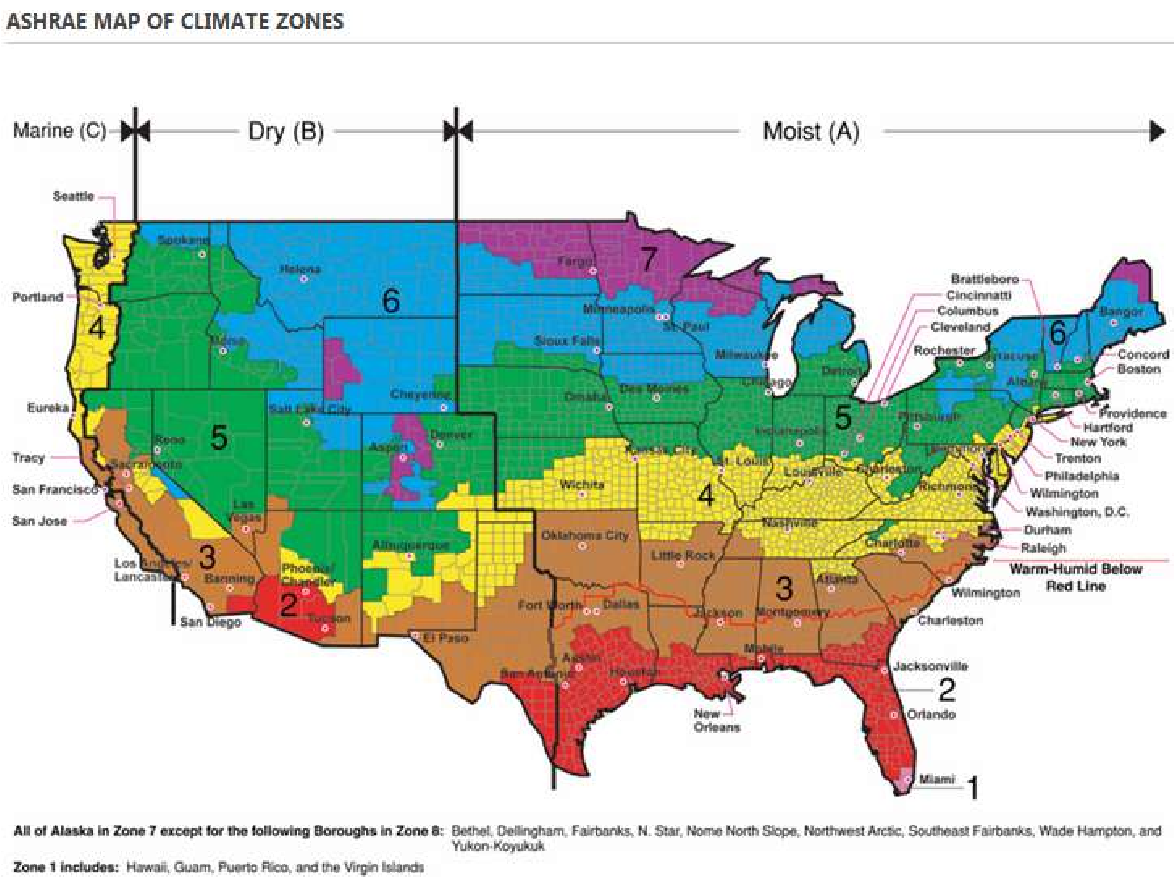


Figure 24 Map of US Climate Zones recognized by ASHRAE

CHAPTER 5

Simulations Result

In this chapter, the calibrated model is used to simulate annual energy consumption for ASHP system, when changing the current ventilation strategy used now in the school building. The change is proposed to be by applying CO_2-DCV to modify amount of ventilation based on space occupancy profile and to combine that with the economizer operation.

To apply demand control ventilation of CO_2 base, each zone in the school needs to be equipped with a CO_2 zone sensor, and these sensors can monitor the CO_2 concentration that reflects occupancy profiles, which could vary from 100% as low as 50%. To apply economizer operation to the model, one of two modes is used based on climate weather. This type is mono dry bulb temperature mode or mono enthalpy mode.

To determine the annual energy use, simulations are carried out for three different cases: (1) *Baseline* (no economizer or CO_2-DCV), (2) when the CO_2-DCV is applied for different occupancy profiles, and (3) when both economizer and CO_2-DCV are applied for different profiles.

To evaluate CO_2-DCV and economizer performance in different climate zones, simulations are performed for 11 United States locations with different climate zones as identified in ASHRAE US Climate Zones. First location analyzed with the proposed strategy is Greensboro NC, which is in climate zone A 4 according to ASHRAE US climate zones; other locations are shown in Table 2 in Chapter 4. The simulation results are shown below for: (1) the city of Greensboro, with detailed heating and cooling energy analysis and additional occupancy profiles, and (2) 10 other USA locations.

5.1 Results for Greensboro City

Simulations are done for Greensboro City, NC using the calibrated model and covering the three different cases described before.

- Simulation result for the *Baseline*. Visual energy simulation result for *Baseline* and when applied the proposed strategy of CO_2-DCV only and both are shown in Appendix A1-4.
- Simulations result when only CO_2-DCV strategy are applied with different occupancy profile 90%, 80%, 75%, 70%, 60% and 50%, and analyzed by comparing it with the *Baseline* results of full occupancy profile to determine the saving obtained. Detailed energy consumption analysis for heating, cooling and total energy use with their saving for the same profiles mentioned above are shown in Table 3.
- Simulations results when both CO_2- DCV strategy and economizer operation are applied for different occupancy from 100% down to 50% to be compared with the full occupancy *Baseline* energy use in Table 4.
- Comparison between *Baseline* energy use, and when the proposed strategy are applied is shown in Figure 5.2.

Detailed results of simulations when the proposed strategy are applied to the *Baseline* for different occupancy profiles; the fan power is not included in the cooling and heating energy consumption analysis, but it does in the total energy consumption as shown in Table 3 and Figure 5.1.

Table 3

Annual energy use (kWh x000) for cooling, heating and total when the CO_2 -DCV is applied for Greensboro.

Occupancy Profile	Cooling	Save w/cooling	Heating	Save w/heating	Total	Save w/total
Baseline	316	No	119	No	1258	No
90%	314	0%	78	35%	1,179	6%
80%	301	5%	75	37%	1,136	10%
75%	294	7%	73	39%	1,114	11%
70%	287	9%	71	40%	1,093	13%
60%	274	13%	68	42%	1,051	16%
50%	261	17%	66	45%	1,009	20%

Table 4

Annual energy consumption (kWh x000) for cooling, heating and total when the CO_2-DCV and economizer are applied for Greensboro

Occupancy Profile	Cooling	Save/cooling	Heating	Save/heating	Total	Save/total
Baseline	316	No	119	No	1,258	No
Both 100% *	276	13%	81	32%	1,171	7%
Both-90%	264	16%	78	35%	1,129	10%
Both-80%	252	20%	75	37%	1,088	14%
Both-75%	246	22%	73	39%	1,067	15%
Both-70%	240	24%	71	40%	1,047	17%
Both-60%	229	28%	68	42%	1,006	20%
Both-50%	217	31%	66	45%	966	23%
* As the occupancy is 100%, the saving is then only resulted from the economizer operation						

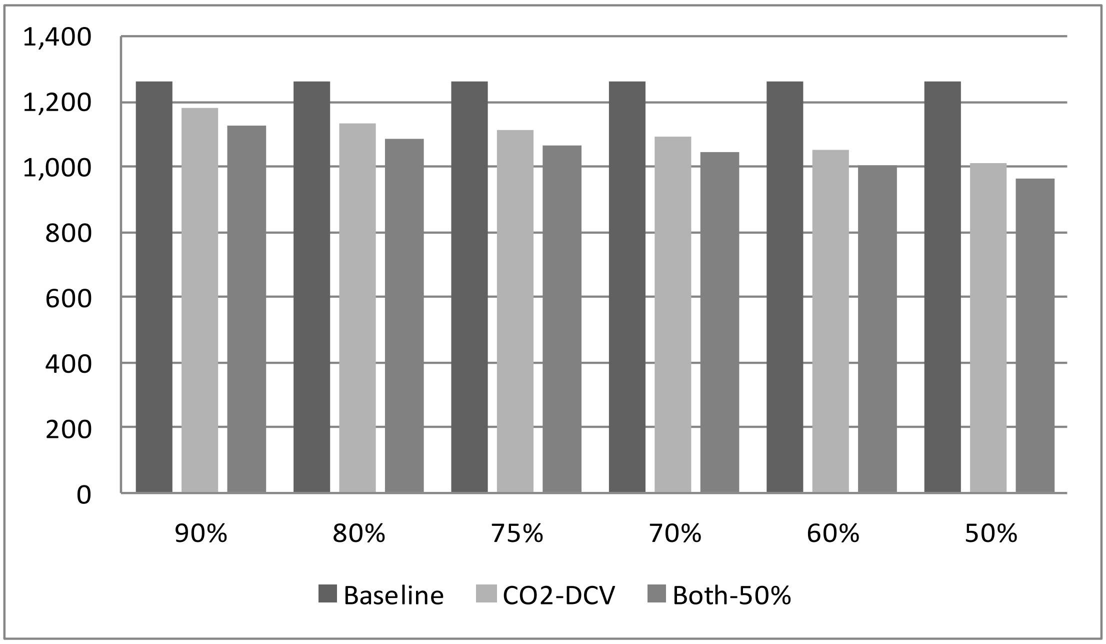


Figure 25 Annual energy use (kWhx000) with the proposed strategy for city of Greensboro with different profiles

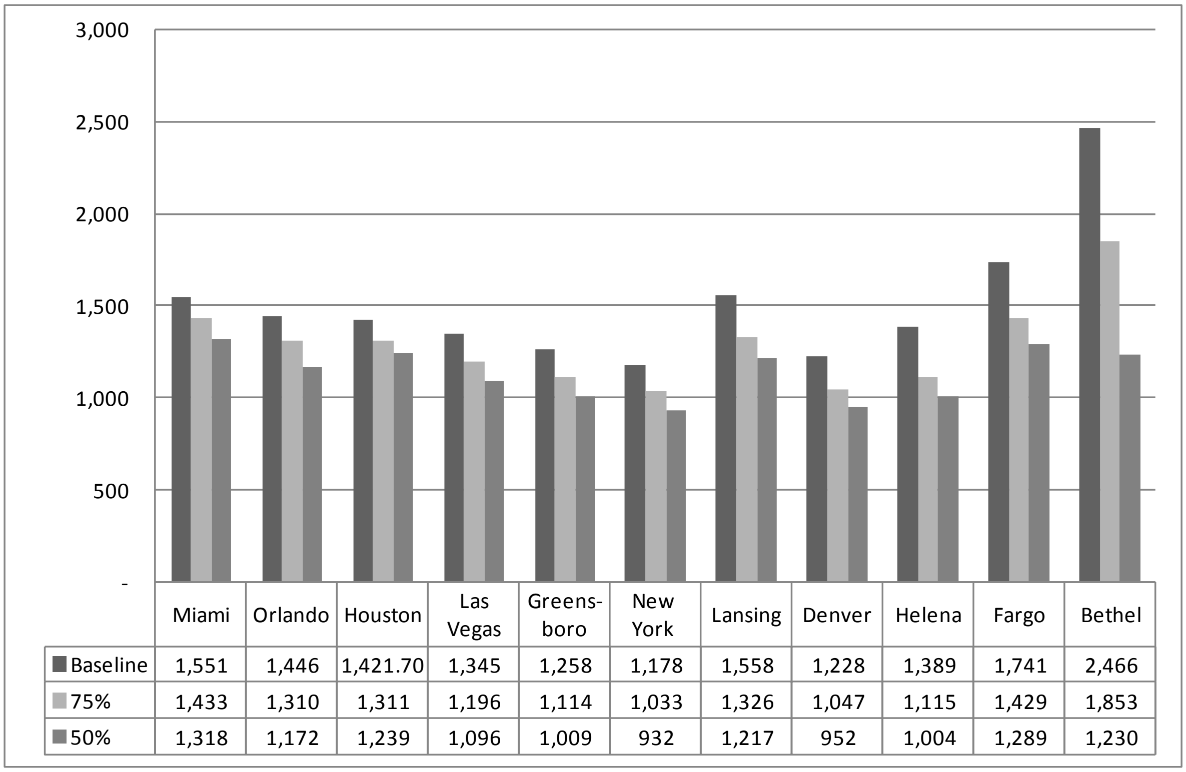
5.1.1 Greensboro Saving Analysis. A significant saving in Greensboro can be achieved by applying the proposed strategy. If the actual occupancy drops to 50% less than design occupancy, the saving becomes 20% when the CO_2-DCV is only applied and it becomes 23% when both economizer and CO_2-DCV are applied.

- Table 3: Indicates the saving for heating is more than cooling due to longer scheduling hours in the winter season than summer break season in school.
- Table 4: Indicates the saving in cooling increases significantly with the proposed strategy due to economizer operation that affect cooling only, and we can notice that the heating is same as without economizer.
- Figure 25: Shows the increasing in saving when combining CO_2-DCV along with economizer.

5.2 Results for various locations

The developed model runs for various locations to predict the annul energy saving due to the proposed strategy (CO_2-DCV only or both CO_2-DCV and economizer). The locations are with different climate zones according to ASHRAE North America Climate Zone Map as in Figure 4.5, locations are detailed in Table 1 Chapter 4. The annual energy uses for each location are simulated for baseline, when the CO_2-DCV is applied and when both CO_2-DCV and economizer are applied. The results are discussed below:

1. Visual simulation results for different locations and profiles (*Baseline* and both with 50% profile) are shown in Appendix B1-20.
2. Simulations results of total energy consumption for various locations with only CO_2-DCV strategy and for 75% and 50% of the design profile are compared with *Baseline* in Figure 26, while the saving obtained from this strategy is shown in Figure 27.
3. Saving when both CO_2-DCV and economizer are applied for various locations and when the occupancy is 100% of design in Figure 28.
4. Simulation results when both CO_2-DCV and economizer are applied with 75%, 50% profiles and for various locations in Figure 29, the saving is shown saving in Figure 30.
5. Table 1 in appendix C, shows the 11 locations simulation results with all the cases of *Baseline* (old and new standard), when only CO_2-DCV applied (for 75and 50% profiles) and when both of CO_2-DCV and economizer applied (for 100, 75 and 50% profiles) with the saving obtained.



	Miami	Orlando	Houston	Las Vegas	Greens-boro	New York	Lansing	Denver	Helena	Fargo	Bethel
Baseline	1,551	1,446	1,421.70	1,345	1,258	1,178	1,558	1,228	1,389	1,741	2,466
75%	1,433	1,310	1,311	1,196	1,114	1,033	1,326	1,047	1,115	1,429	1,853
50%	1,318	1,172	1,239	1,096	1,009	932	1,217	952	1,004	1,289	1,230

Figure 26 Annual Energy Consumption (kWh x 000) with *CO_2-DCV* Strategy for various locations with 75% and 50% profile of design occupancy

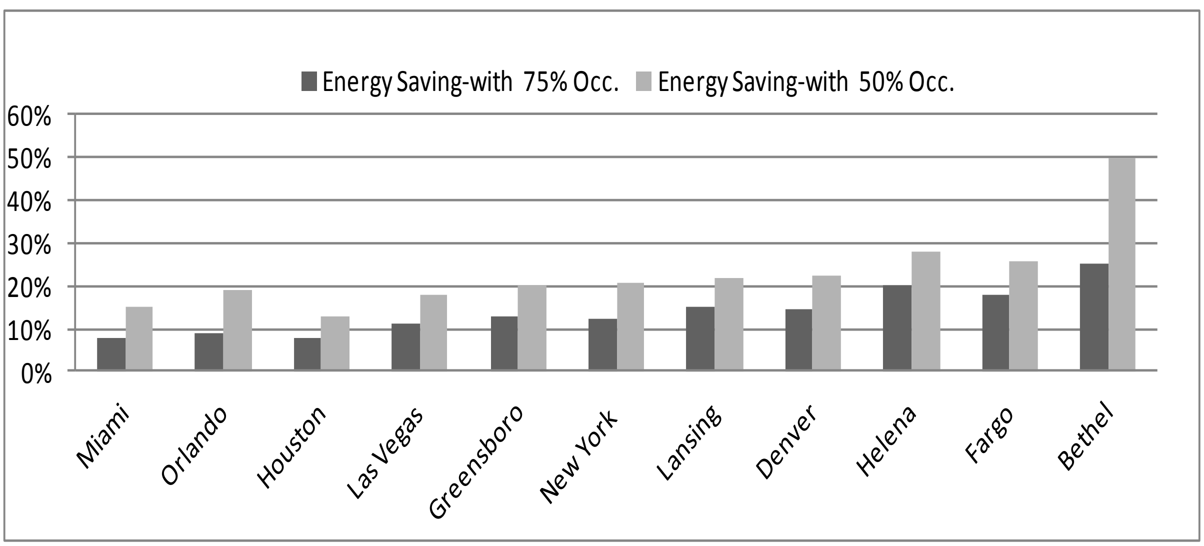


Figure 27 Saving in (kWhx000) with only CO_2-DCV Strategy for various locations with 75% and 50% profile of design occupancy

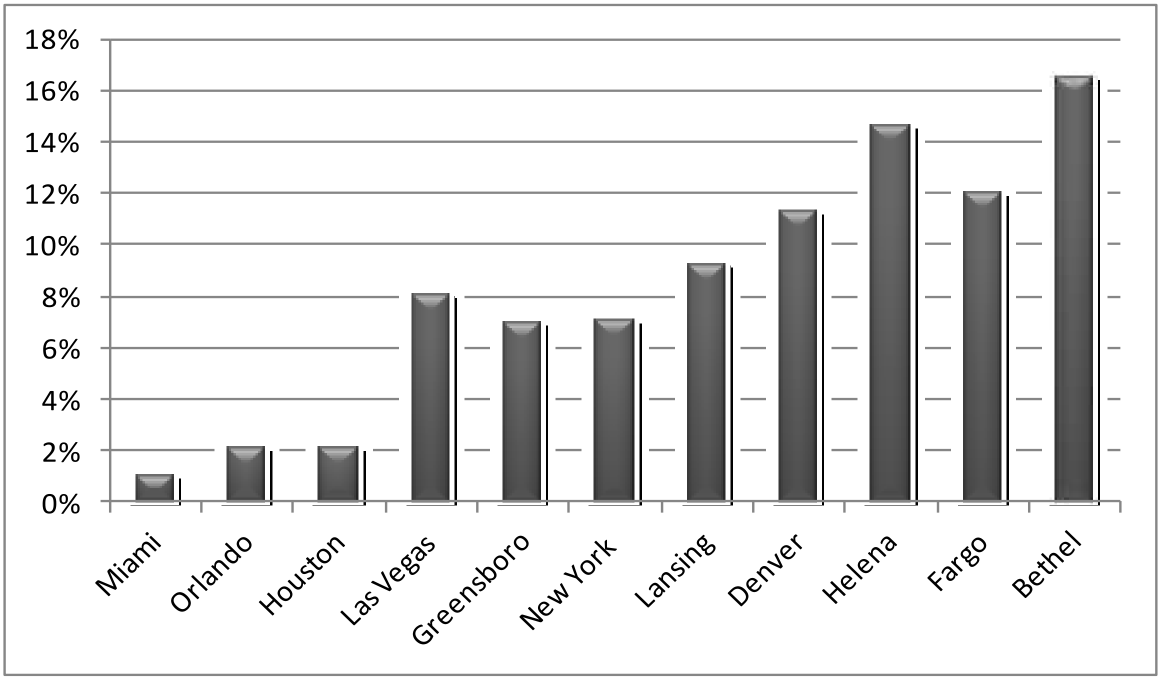
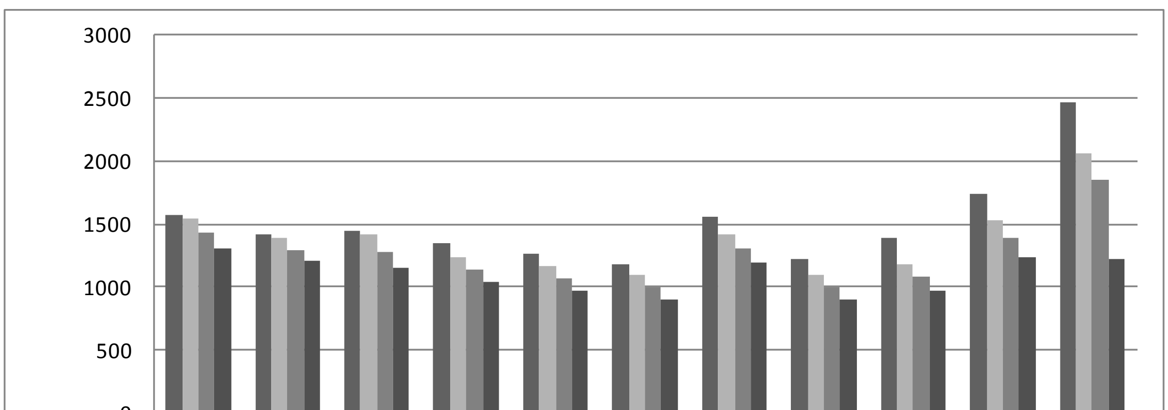


Figure 28 Annual energy saving due to economizer affections when doth are applied with full occupancy and for various locations



	Miami	Orlando	Houston	Las Vegas	Greens-boro	New York	Lansing	Denver	Helena	Fargo	Bethel
Baseline	1566	1422	1446	1345	1258	1178	1558	1228	1389	1741	2466
100%	1544	1392	1417	1238	1171	1095	1416	1090	1187	1532	2058
75%	1426	1288	1282	1137	1067	995	1301	997	1076	1384	1850
50%	1311	1214	1146	1041	966	897	1192	907	969	1242	1226

Figure 29 Annual energy use (kWhx000) with both of CO_2-DCV and economizer for various locations with 75% and 50% profile of design occupancy

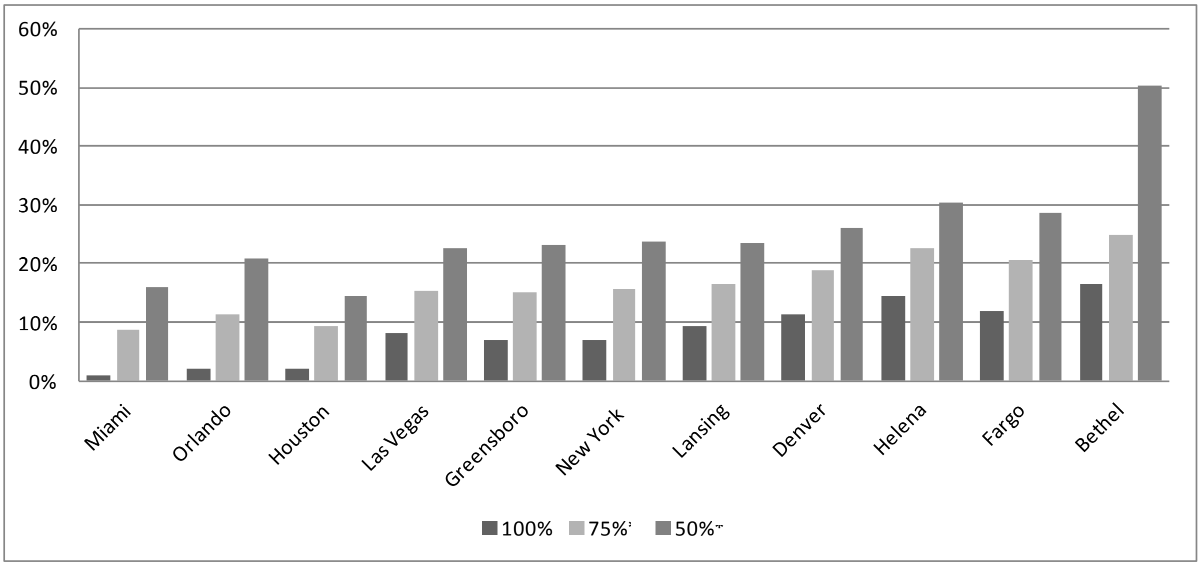


Figure 30 Saving in (kWhx000) with both of CO_2-DCV and economizer for various locations with full, 75% and 50% profile of design occupancy.

CHAPTER 6

Conclusion and Future Work

6.1 Summary of the study

A 133,200 ft^2 middle school equipped with air source heat pumps is investigated in this study. The school is first modeled using the whole building simulation energy software e-Quest. The model was calibrated using utility data of year 2009 and then tested on other utility data covering four years. The calibrated and tested results showed that the model produces accurate estimations and the error is less than 5%. The calibrated model then used to determine the energy savings for the building when upgrade HVAC system with a strategy proposed by this study.

The proposed strategy improves air source heat pump efficiency by combining demand control ventilation and economizer operation. Demand control ventilation was used to adjust ventilation load base on occupancy profile, while economizer operation was used outdoor free cooling to reduce mechanical cooling operation in moderated weather. Simulations for annual energy use were done by the model for each case and with different occupancy profile to determine the saving obtained from each case. A CO_2-DCV model was developed through deriving equations to determine amount of ventilation required for each zone in multi zone building system.

6.2 Conclusion

Over hundred simulation runs were carried out for different USA locations and occupancy profiles and by integrating the proposed CO_2-DCV and economizer. The results showed that a significant energy saving can be achieved. This saving varies according to the locations and actual occupancy profile drifted from the design occupancy. The outcome conclusions obtained from analyzing simulation results for the proposed strategy, can be recommended to the school. In addition, these conclusions can be added to the previous researches that had been done before this work about demand control ventilation.

6.2.1 Conclusions for CO_2-DCV and Economizer Individually

- The reliable simulation model was created in e-Quest and was calibrated with real existing building data and updated with the new ASHRAE 62.1-2010 specifications can predict accurate energy use whenever the model modified, by compare simulation results with results of other studies. Using a simulation model in research to investigate the effect of any modification done to the base model is easier and cheaper research.
- Energy saving obtained from CO_2 demand control ventilation can be significant and it varies based on occupancy profile and climate zone. Saving obtained from total energy used for a school building with 133,200 ft^2 and with half of design occupancy is 8% for Miami, 9% for Orlando & Houston, 11% for Las Vegas, 13% for Greensboro, 12% for New York, 15% for Lansing and Denver, 20% for Helena, 18% for Fargo and 25% for Bethel in Alaska climate weather.
- Energy saving obtained from the both of CO_2-DCV and economizer with full design profile is due to the effect of economizer operation. and it varies with different climate weather zone; the saving is 1% for Miami, 29% for Orlando, 3% Houston, 8% for Las Vegas, 7% for Greensboro & New York, 9% foe Lansing, 11% Denver, 15% for Helena, 12% for Fargo and 17% for Bethel in Alaska.
- The saving in total energy use is significant in this type of buildings due to the dominated effect of HVAC system and it is more than the half of total energy consumption. That's because an efficient lighting system of occupants and the use of day lighting in this

building. The other reason to have a big saving in total is that, e-Quest minimize the load oh hot water when minimize

6.2.2 Conclusions of Combining CO2-DCV and Economizer. Energy saving obtained from the proposed strategy by combining CO2-DCV and economizer operation with half of design profile are 16% for Miami, 21% for Orlando, 16% Houston, 23% for Las Vegas, 23% for Greensboro, 24% for New York, 24% for Lansing, 26% Denver, 30% for Helena, 29% for Fargo and 50% for Bethel in Alaska.

- Saving amount when combining the both are more in 2 or 3 points than saving amount when CO_2-DCV is the only applied. For instance saving amount for the city of Greensboro with CO_2-DCV only and half design of occupancy is 20% while with both and half of design of occupancy is 23%. The reason why this amount is not more for the booth is because of the deactivation of the CO_2-DCV strategy by the economizer operation.
- From heating and cooling analysis for Greensboro, cooling saving with CO2-DCV would increases with the presences of economizer, while heating load is not be affected.

6.3 Future Work

For further studies that are related to improve the efficiency of HVAC system, by reducing occupant's load, more investigations in these fields and would be suggested:

- Calculations work out are required to determine CO_2 Concentration in the zone, when multi zone system that complies with the new standards of ASHRAE 62.1-2010.
- The possibility of combining another type of ventilations control strategies such as Displacement Ventilation and Dedicated Outdoor Air System with the Demand Control Ventilation and the affections of them on the energy use.

- Type of controller is very important and how can it works when integrating more than one ventilation control strategy.
- Spaces with different activities type how they affect the accuracy return zone's sensors readings.
- Sensor's locations (zone or return duct sensors), the impact of both of them on readings accuracy and the saving are obtained.

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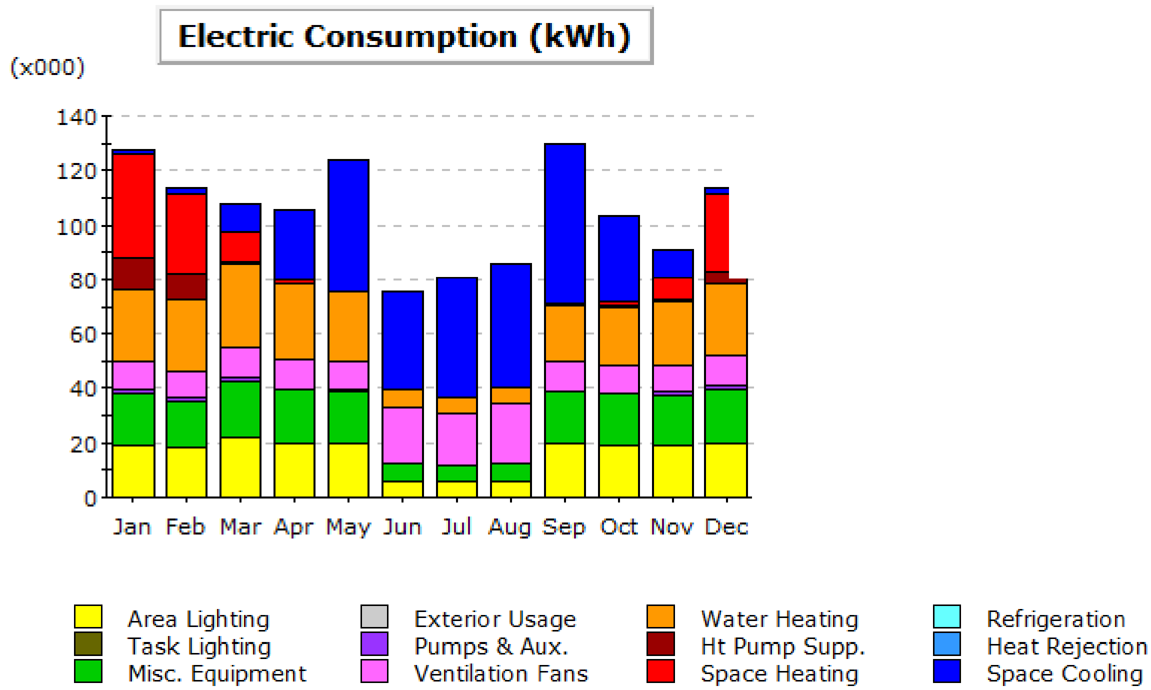
Appendix A

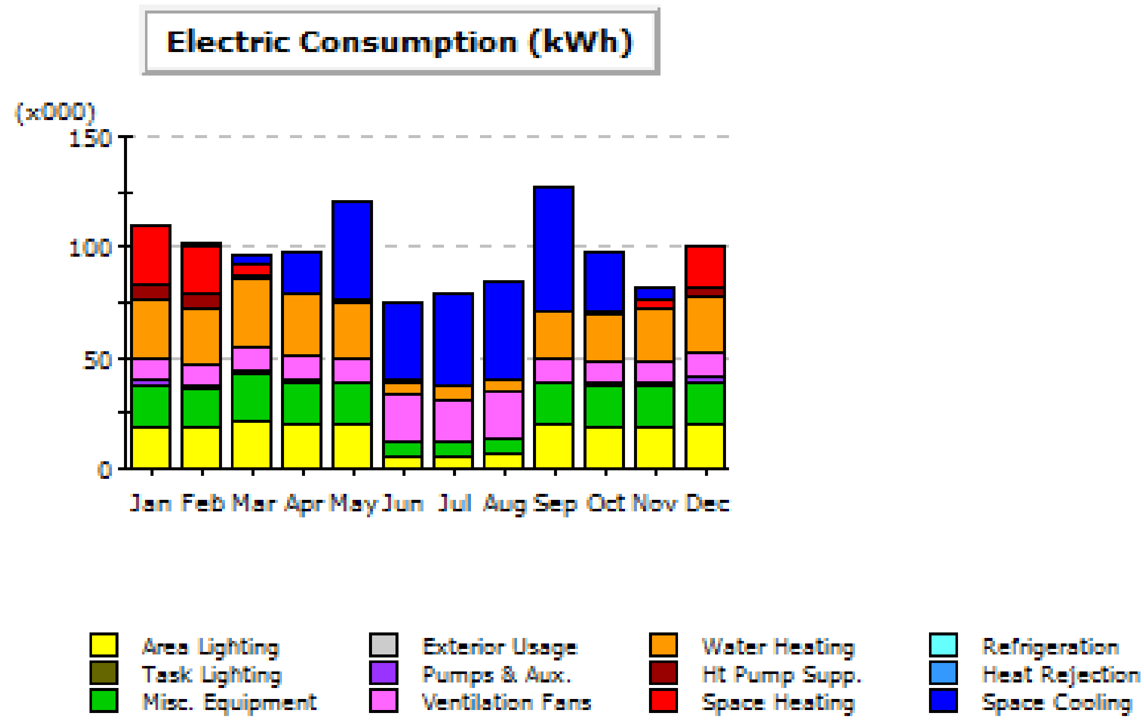
Visual of simulations for Greensboro City



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.9	2.3	10.1	26.0	48.4	36.0	44.0	45.3	59.2	31.6	9.9	2.1	315.7
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	38.2	29.4	10.5	1.1	0.2	0.2	0.1	0.1	0.2	1.6	8.6	28.7	118.9
HP Supp.	11.6	9.6	0.8	0.0	-	-	-	-	-	0.1	0.7	4.8	27.6
Hot Water	26.7	26.0	30.9	27.9	25.8	6.5	5.8	6.1	21.2	21.4	23.0	26.2	247.5
Vent. Fans	10.2	9.5	11.4	10.7	10.5	20.6	18.9	21.5	10.4	10.2	10.0	10.7	154.6
Pumps & Aux.	1.8	1.4	1.3	0.6	0.1	0.0	-	-	0.0	0.6	1.2	1.9	8.9
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	127.2	113.8	107.4	105.6	124.2	75.6	80.9	85.7	130.1	103.2	90.8	113.7	1,258.3

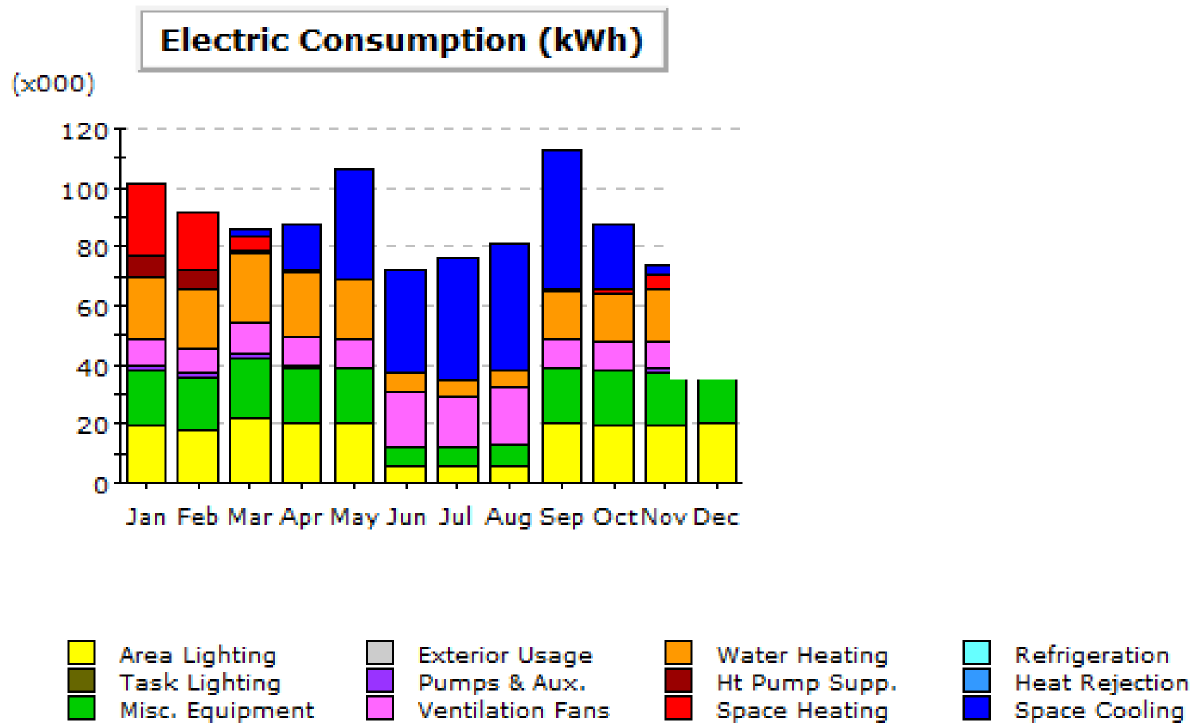
Figure A.1. Simulation for *Baseline* (Greensboro)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.6	3.8	18.6	44.0	35.5	41.8	43.9	56.1	26.7	4.6	0.1	275.6
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	26.6	21.4	5.7	0.9	0.5	0.1	0.1	0.1	0.6	1.3	4.9	18.7	81.0
HP Supp.	6.9	6.6	0.5	0.0	-	-	-	-	-	0.0	0.3	2.9	17.3
Hot Water	26.7	26.0	30.9	27.9	25.8	6.5	5.8	6.1	21.2	21.4	23.0	26.2	247.5
Vent. Fans	10.2	9.5	11.4	10.7	10.5	20.6	18.9	21.5	10.4	10.2	10.0	10.7	154.6
Pumps & Aux.	2.0	1.6	1.4	0.6	0.1	0.0	-	-	0.0	0.6	1.3	2.0	9.6
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	110.2	101.2	96.1	98.0	120.1	75.1	78.7	84.3	127.3	98.0	81.5	100.1	1,170.6

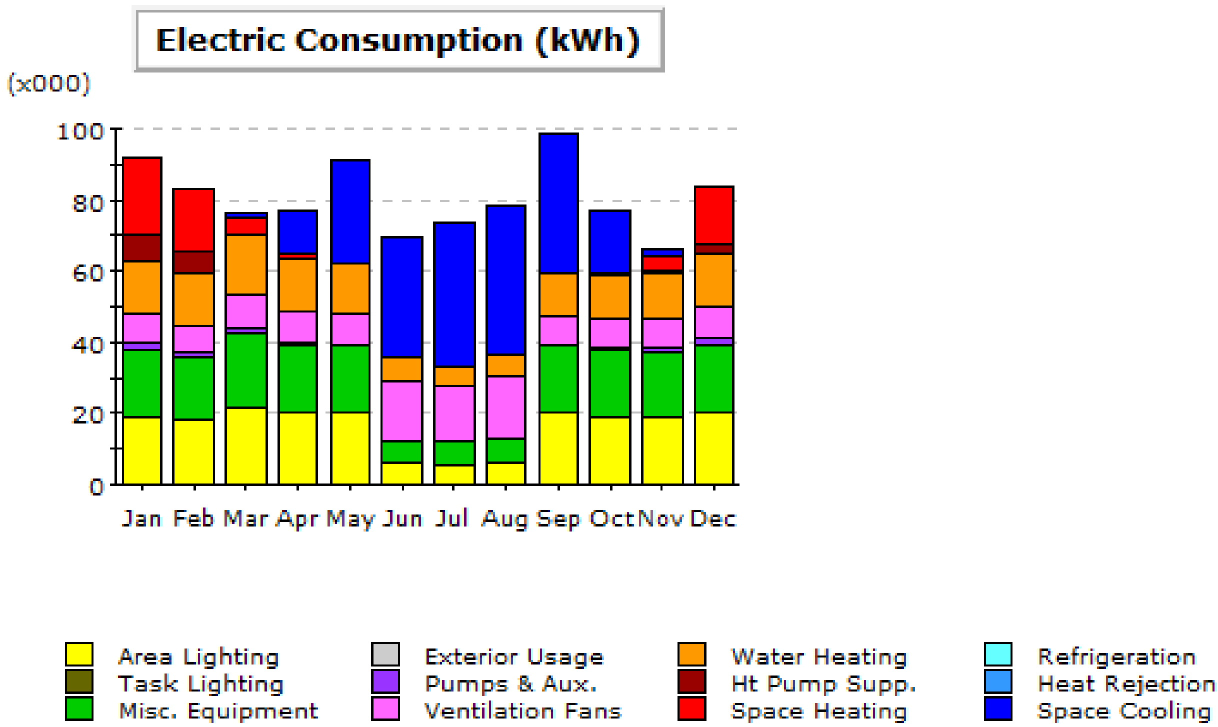
Figure A.2. Simulation when both are applied with 100% profile (Greensboro).



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.3	2.6	15.3	36.7	34.5	40.8	42.8	47.7	22.1	3.2	0.0	246.2
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	24.3	19.2	5.0	0.8	0.4	0.1	0.1	0.1	0.4	1.1	4.3	17.3	72.9
HP Supp.	7.0	6.6	0.4	0.0	-	-	-	-	-	0.0	0.3	2.9	17.3
Hot Water	20.8	20.1	23.8	21.5	19.9	6.5	5.8	6.1	16.4	16.6	17.8	20.4	195.8
Vent. Fans	9.3	8.6	10.3	9.7	9.5	18.7	17.1	19.4	9.5	9.3	9.1	9.7	140.1
Pumps & Aux.	2.0	1.6	1.5	0.6	0.1	0.0	-	-	0.0	0.6	1.3	2.0	9.7
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	101.1	92.0	86.0	87.2	105.8	72.1	76.0	81.2	113.0	87.5	73.5	91.7	1,067.0

Figure A.3. Simulation when both are applied with 75% profile (Greensboro).



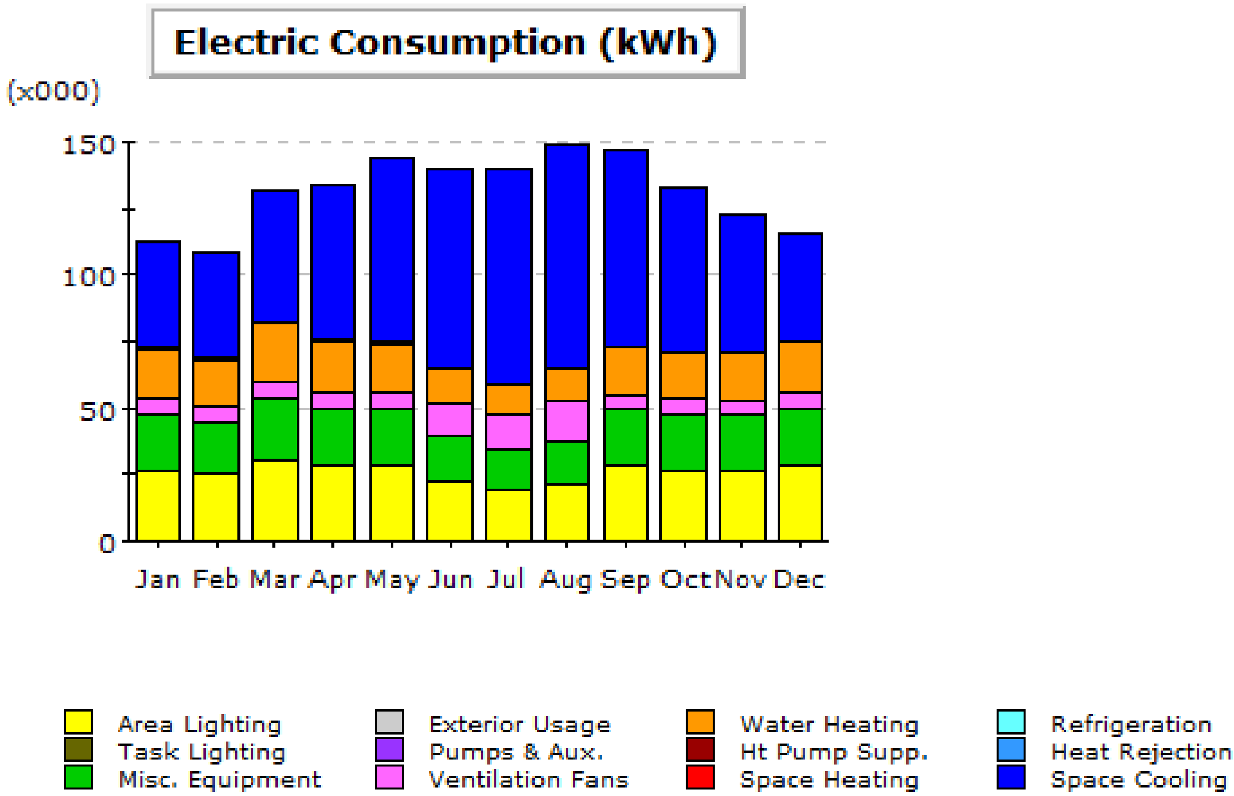
Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.04	0.21	1.77	12.26	29.32	33.56	39.99	41.76	38.84	17.35	2.23	0.01	217.34
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	21.95	17.01	4.43	0.76	0.28	0.11	0.06	0.06	0.32	0.85	3.93	15.83	65.59
HP Supp.	7.07	6.62	0.43	0.00	-	-	-	-	-	0.04	0.36	3.04	17.57
Hot Water	14.87	14.28	16.76	15.17	13.99	6.49	5.85	6.09	11.55	11.88	12.69	14.56	144.17
Vent. Fans	8.34	7.78	9.27	8.71	8.56	16.80	15.44	17.51	8.53	8.34	8.15	8.71	126.15
Pumps & Aux.	2.00	1.56	1.47	0.65	0.12	0.01	-	-	0.03	0.59	1.32	2.05	9.80
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.55	17.41	20.70	19.19	19.21	6.52	6.44	6.76	19.11	18.55	18.36	19.29	190.09
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.23	18.13	21.74	20.07	19.99	5.82	5.64	6.04	19.95	19.23	19.07	20.11	195.01
Total	92.04	83.00	76.56	76.81	91.46	69.32	73.42	78.23	98.32	76.82	66.13	83.60	965.72

Figure A.4. Simulation when both are applied with 50% profile (Greensboro).

Appendix B

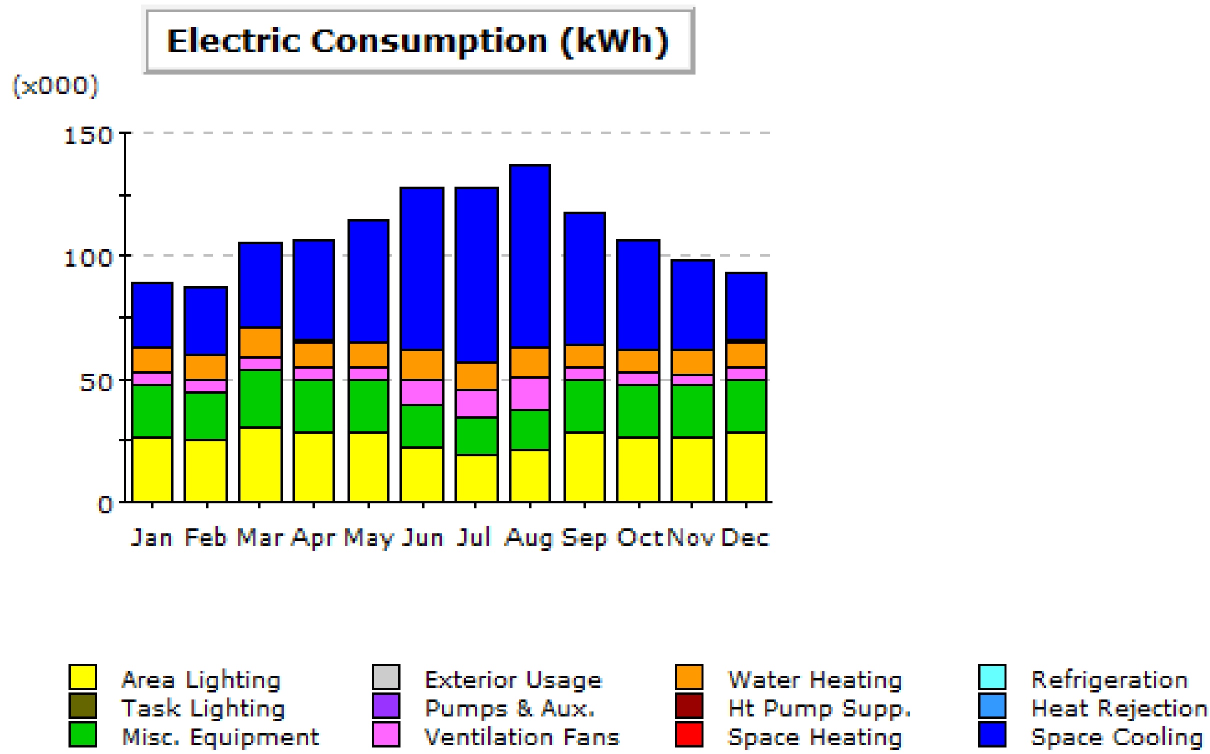
Visual of simulations for various locations



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	39.2	40.3	49.5	57.8	68.9	75.3	81.1	85.0	74.2	62.0	52.0	40.4	725.6
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.5	0.1	0.2	0.4	0.3	0.0	-	-	0.1	0.2	0.2	0.0	2.0
HP Supp.	0.0	-	-	-	-	-	-	-	-	-	-	-	0.0
Hot Water	19.0	18.2	21.8	19.8	19.1	13.4	11.1	12.1	17.6	17.2	17.7	19.3	206.4
Vent. Fans	5.5	5.2	6.2	5.8	5.7	12.3	13.6	14.4	5.7	5.5	5.4	5.8	90.9
Pumps & Aux.	0.1	0.0	0.0	-	-	-	-	-	-	-	-	0.0	0.2
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	20.9	19.6	23.3	21.7	21.7	17.3	15.5	16.9	21.6	20.9	20.7	21.8	241.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	26.8	25.3	30.5	28.0	28.0	21.8	18.8	21.1	27.9	26.8	26.7	28.0	309.7
Total	112.1	108.8	131.5	133.4	143.6	140.2	139.9	149.5	147.0	132.7	122.7	115.3	1,576.7

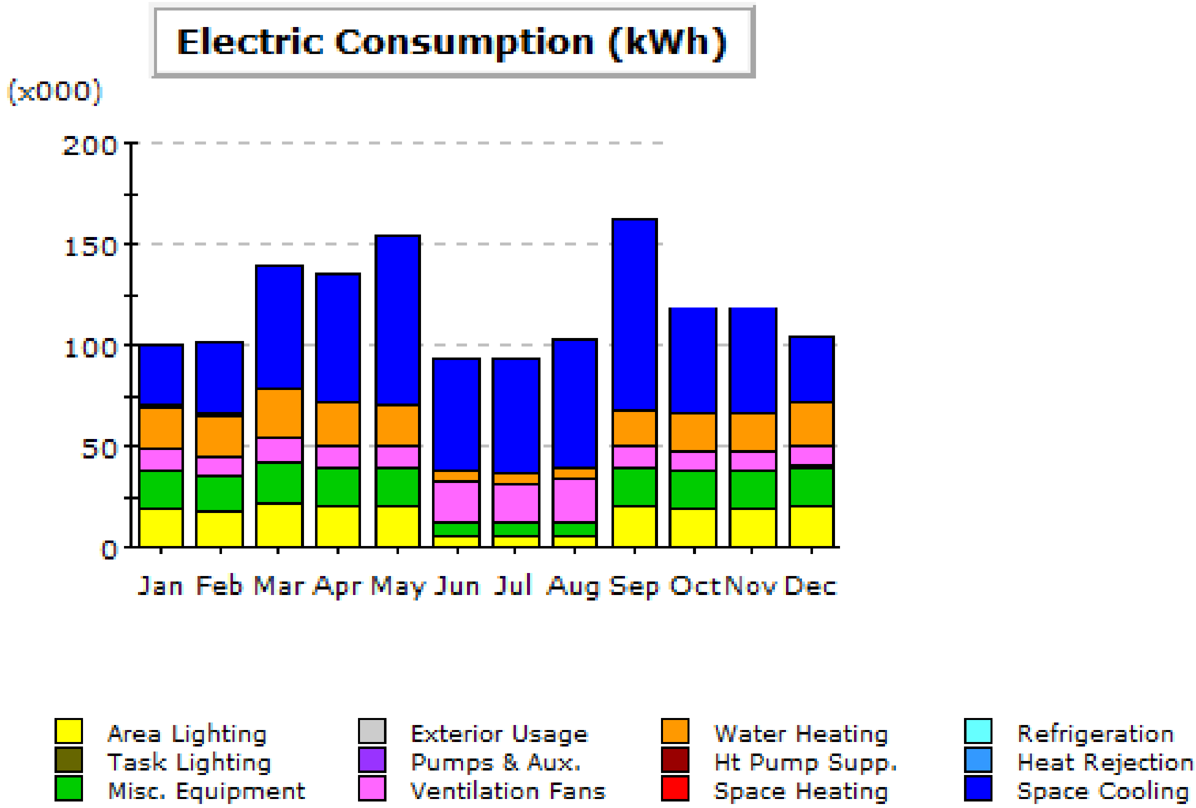
Figure B.1. Simulation for *Baseline* (Miami)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	26.2	27.5	34.0	41.3	49.8	65.9	71.0	74.7	53.5	44.1	36.4	28.1	552.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.2	0.1	0.2	0.1	0.1	0.0	-	-	0.0	0.1	0.1	0.1	1.1
HP Supp.	0.0	-	-	-	-	-	-	-	-	-	-	-	0.0
Hot Water	10.5	9.9	11.8	10.8	10.4	11.8	11.1	12.1	9.6	9.5	9.7	10.6	127.7
Vent. Fans	4.7	4.4	5.3	4.9	4.8	10.5	11.5	12.2	4.8	4.7	4.6	4.9	77.4
Pumps & Aux.	0.1	0.0	0.0	-	-	-	-	-	-	-	-	0.0	0.2
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	20.9	19.6	23.3	21.7	21.7	17.3	15.5	16.9	21.6	20.9	20.7	21.8	241.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	26.8	25.3	30.5	28.0	28.0	21.8	18.8	21.1	27.9	26.8	26.7	28.0	309.7
Total	89.4	86.9	105.0	106.8	114.8	127.3	127.9	137.0	117.4	106.1	98.3	93.5	1,310.5

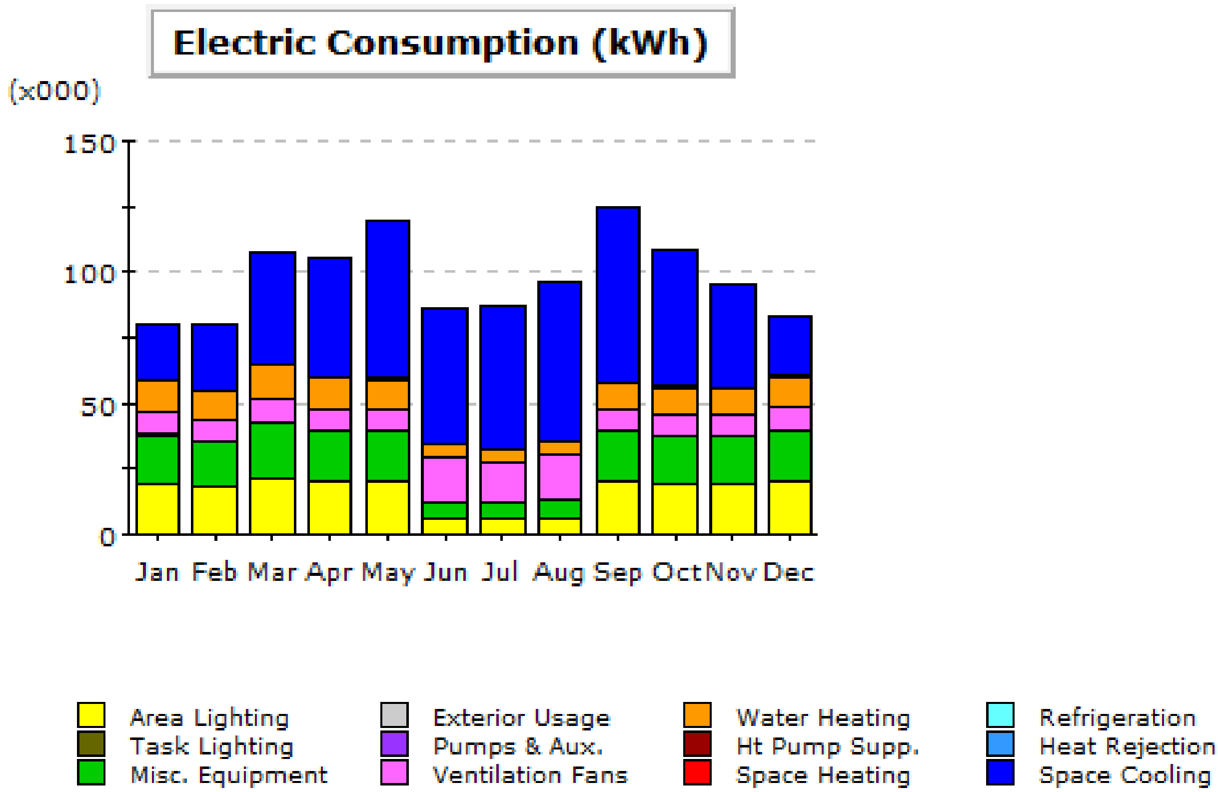
Figure B.2. Simulation when both are applied with 50% profile (Miami).



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	29.4	36.0	60.2	62.2	83.1	54.8	56.9	63.8	94.0	73.7	56.1	31.8	702.0
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.7	0.2	0.5	0.4	0.2	0.0	0.0	0.0	0.0	0.2	0.4	0.5	3.1
HP Supp.	0.0	0.0	-	-	-	-	-	-	-	-	-	0.0	0.0
Hot Water	21.0	20.2	24.1	21.9	20.8	5.5	5.1	5.4	18.4	18.2	18.9	21.1	200.5
Vent. Fans	10.2	9.5	11.3	10.6	10.4	20.5	18.8	21.4	10.4	10.2	9.9	10.6	153.9
Pumps & Aux.	0.6	0.2	0.1	0.0	-	-	-	-	-	-	0.0	0.5	1.4
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	99.6	101.6	138.7	134.5	153.7	93.2	92.9	103.3	161.8	140.1	122.8	103.8	1,446.0

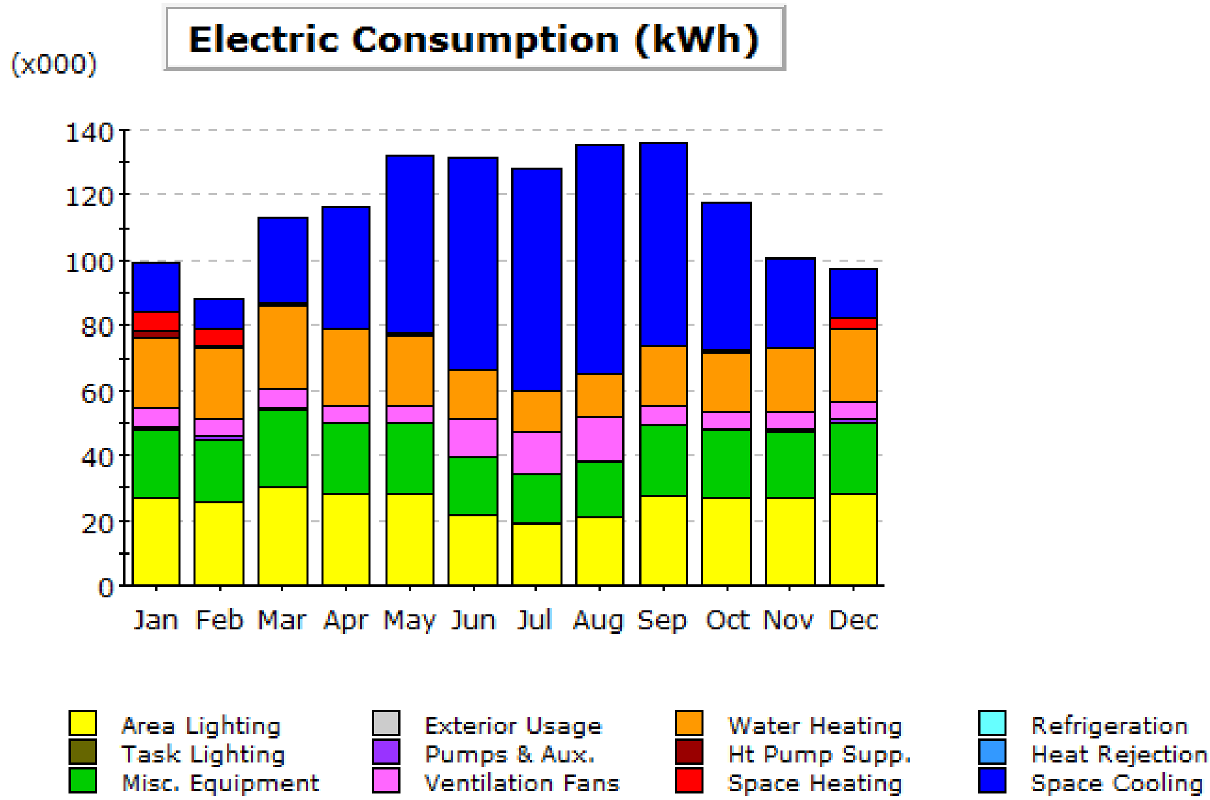
Figure B.3. Simulation for *Baseline* (Orlando)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	21.0	25.2	42.2	44.7	59.9	52.0	54.4	60.9	67.0	52.3	39.4	22.5	541.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	0.3	0.1	0.2	0.4	0.3	0.0	0.0	0.0	0.0	0.3	0.2	0.2	1.9
HP Supp.	0.0	0.0	-	-	-	-	-	-	-	-	-	0.0	0.0
Hot Water	11.7	11.1	13.1	12.0	11.3	5.5	5.1	5.4	10.0	10.1	10.4	11.7	117.4
Vent. Fans	8.3	7.7	9.2	8.6	8.5	16.7	15.3	17.4	8.5	8.3	8.1	8.6	125.2
Pumps & Aux.	0.6	0.2	0.1	0.0	-	-	-	-	-	-	0.0	0.5	1.3
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	79.6	79.8	107.2	105.0	119.2	86.5	86.9	96.5	124.5	108.7	95.6	82.9	1,172.3

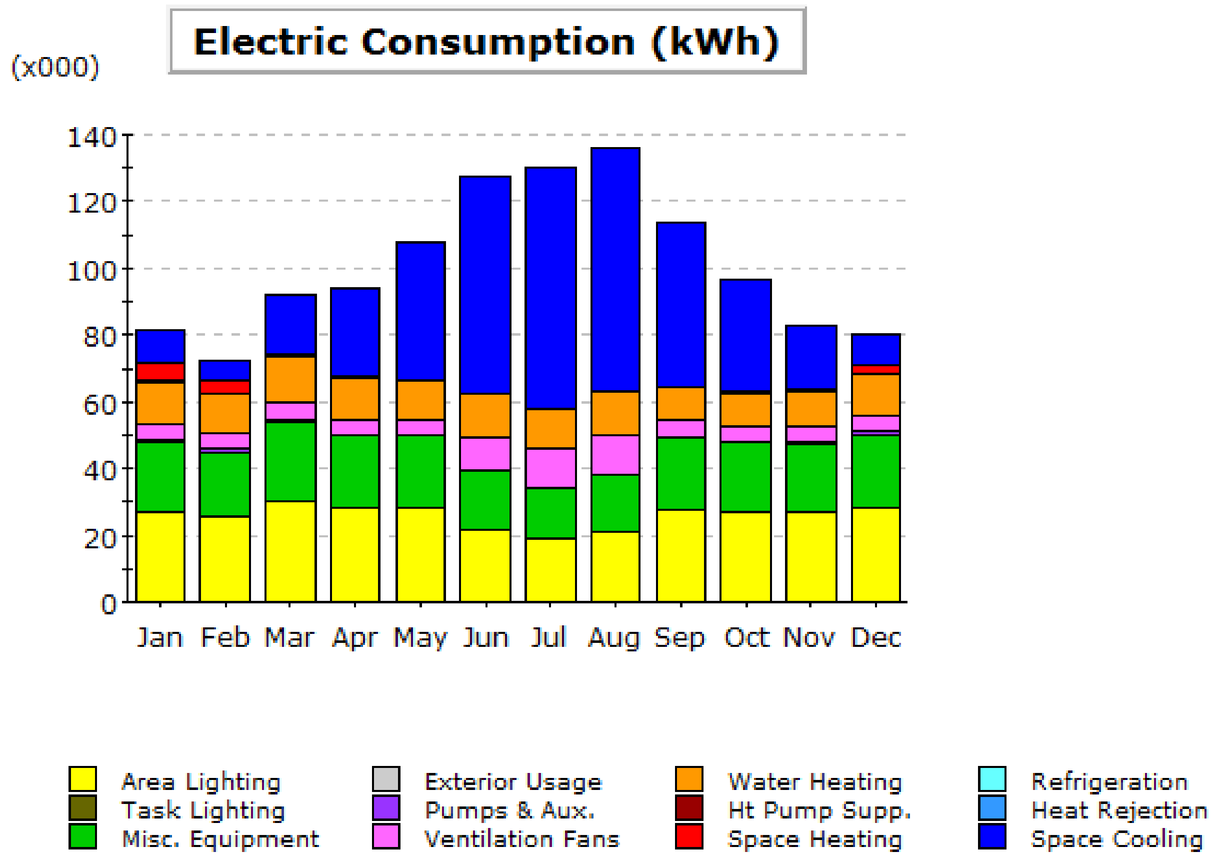
Figure B.4. Simulation when both are applied with 50% profile (Orlando)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	14.9	8.9	26.0	37.2	54.5	65.0	68.8	70.2	62.0	45.3	27.3	14.8	495.0
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	6.1	5.5	0.6	0.2	0.3	0.0	0.0	-	0.1	0.4	0.3	3.0	16.5
HP Supp.	1.5	0.7	0.0	-	-	-	-	-	-	-	0.0	0.3	2.6
Hot Water	22.3	21.7	25.9	23.4	21.9	14.9	11.9	12.8	18.6	18.6	19.6	22.2	233.6
Vent. Fans	5.4	5.1	6.1	5.7	5.6	12.2	13.4	14.2	5.6	5.4	5.4	5.7	89.9
Pumps & Aux.	1.1	1.0	0.5	0.1	0.0	-	-	-	-	0.1	0.4	1.1	4.3
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	20.9	19.6	23.3	21.7	21.7	17.3	15.5	16.9	21.6	20.9	20.7	21.8	241.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	26.8	25.3	30.5	28.0	28.0	21.8	18.8	21.1	27.9	26.8	26.7	28.0	309.7
Total	99.1	87.9	112.9	116.2	131.9	131.1	128.3	135.1	135.8	117.5	100.5	97.0	1,393.5

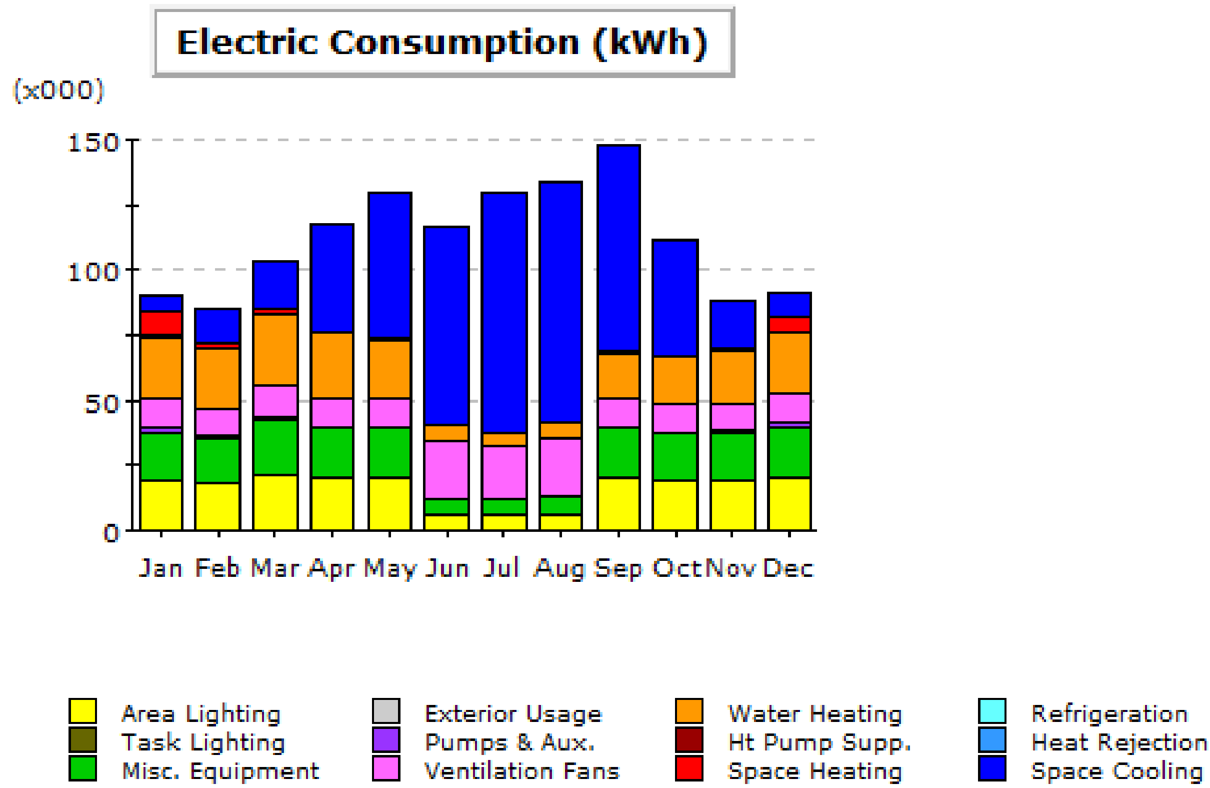
Figure B.5. Simulation for *Baseline* (Houston)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	10.0	5.9	17.9	26.8	41.6	64.8	72.4	73.5	49.1	33.5	19.2	9.7	424.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	4.9	3.9	0.5	0.1	0.2	0.0	0.0	0.0	0.2	0.2	0.2	2.5	12.8
HP Supp.	0.8	0.4	0.0	-	-	-	-	-	-	-	0.0	0.2	1.4
Hot Water	12.3	11.9	14.0	12.7	11.8	13.1	11.9	12.8	10.1	10.2	10.8	12.2	143.6
Vent. Fans	4.7	4.4	5.2	4.9	4.8	10.4	11.5	12.2	4.8	4.7	4.6	4.9	76.8
Pumps & Aux.	1.1	1.1	0.5	0.1	0.0	-	-	-	-	0.1	0.4	1.2	4.5
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	20.9	19.6	23.3	21.7	21.7	17.3	15.5	16.9	21.6	20.9	20.7	21.8	241.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	26.8	25.3	30.5	28.0	28.0	21.8	18.8	21.1	27.9	26.8	26.7	28.0	309.7
Total	81.5	72.6	91.9	94.2	108.1	127.5	130.0	136.4	113.7	96.4	82.6	80.5	1,215.2

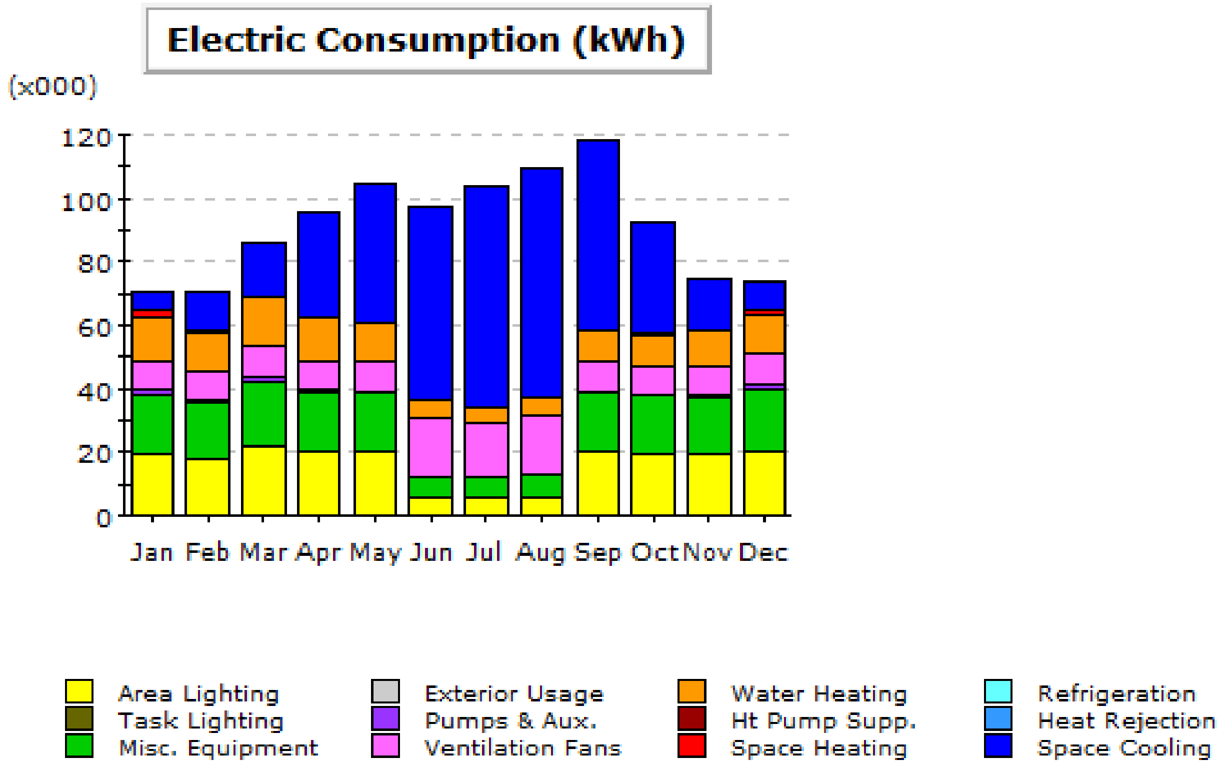
Figure B.6. Simulation when both are applied with 50% profile (Houston)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	5.8	13.2	18.4	41.9	56.1	76.5	92.3	92.6	79.8	44.6	18.7	9.4	549.3
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	9.3	1.5	1.3	0.1	0.3	0.0	-	0.0	0.5	0.2	0.5	5.7	19.4
HP Supp.	0.6	0.1	0.0	-	-	-	-	-	-	-	0.0	0.3	1.1
Hot Water	23.8	23.2	27.8	25.0	22.7	5.6	4.9	5.1	17.7	18.2	19.9	23.0	216.8
Vent. Fans	11.0	10.3	12.3	11.5	11.3	22.2	20.4	23.2	11.3	11.0	10.8	11.5	166.8
Pumps & Aux.	1.9	1.0	1.1	0.1	0.1	-	-	-	-	0.1	0.9	1.7	6.8
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	90.1	84.8	103.3	117.8	129.7	116.6	129.7	133.6	148.3	111.8	88.2	91.2	1,345.1

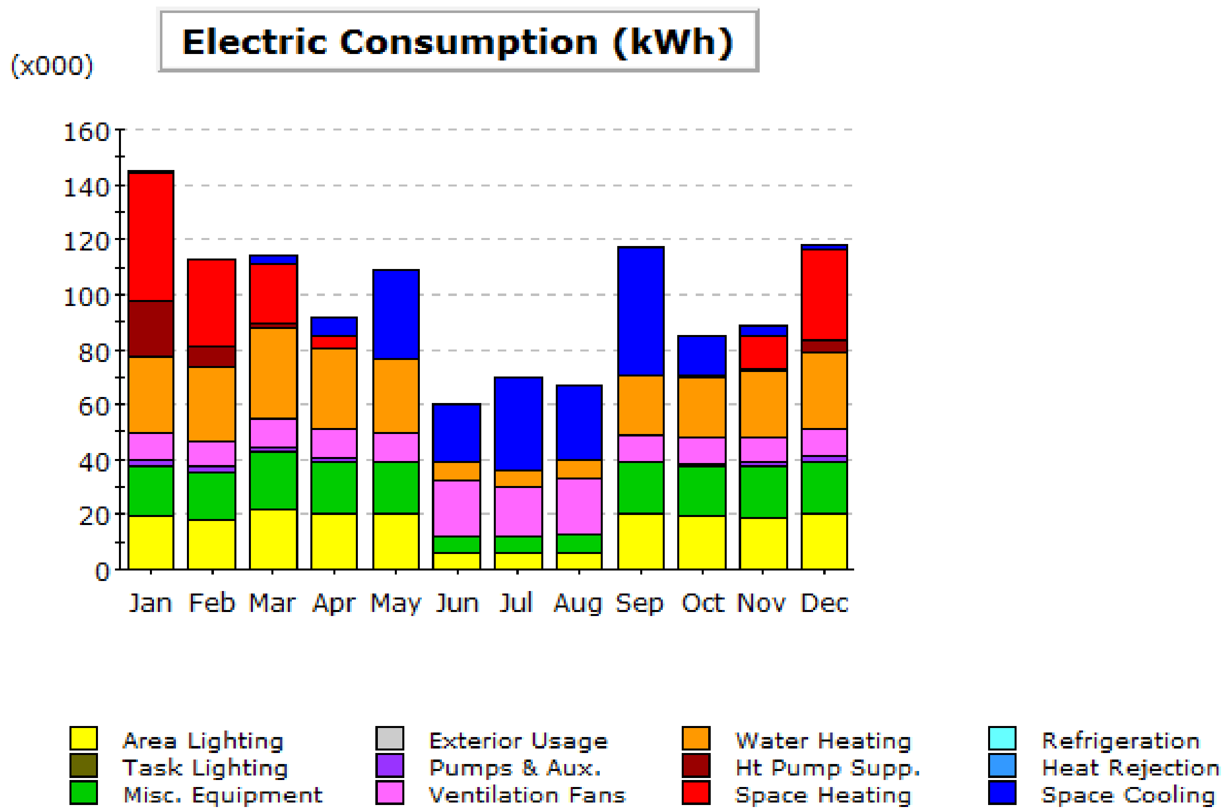
Figure B.7. Simulation for *Baseline* (Las Vegas)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	5.6	12.4	17.2	33.0	43.3	60.8	70.0	72.4	59.9	34.8	16.6	9.0	435.0
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	2.5	0.3	0.2	0.2	0.1	-	-	0.0	0.1	0.3	0.1	0.9	4.6
HP Supp.	0.1	0.0	0.0	-	-	-	-	-	-	-	0.0	0.0	0.2
Hot Water	13.2	12.7	15.1	13.6	12.3	5.6	4.9	5.1	9.6	10.1	11.0	12.8	126.1
Vent. Fans	9.1	8.5	10.2	9.6	9.4	18.4	16.9	19.2	9.3	9.1	8.9	9.6	138.3
Pumps & Aux.	2.0	1.0	1.0	0.1	0.1	-	-	-	-	0.1	0.9	1.8	7.0
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	70.4	70.4	86.1	95.6	104.4	97.2	103.9	109.5	118.0	92.2	75.0	73.5	1,096.3

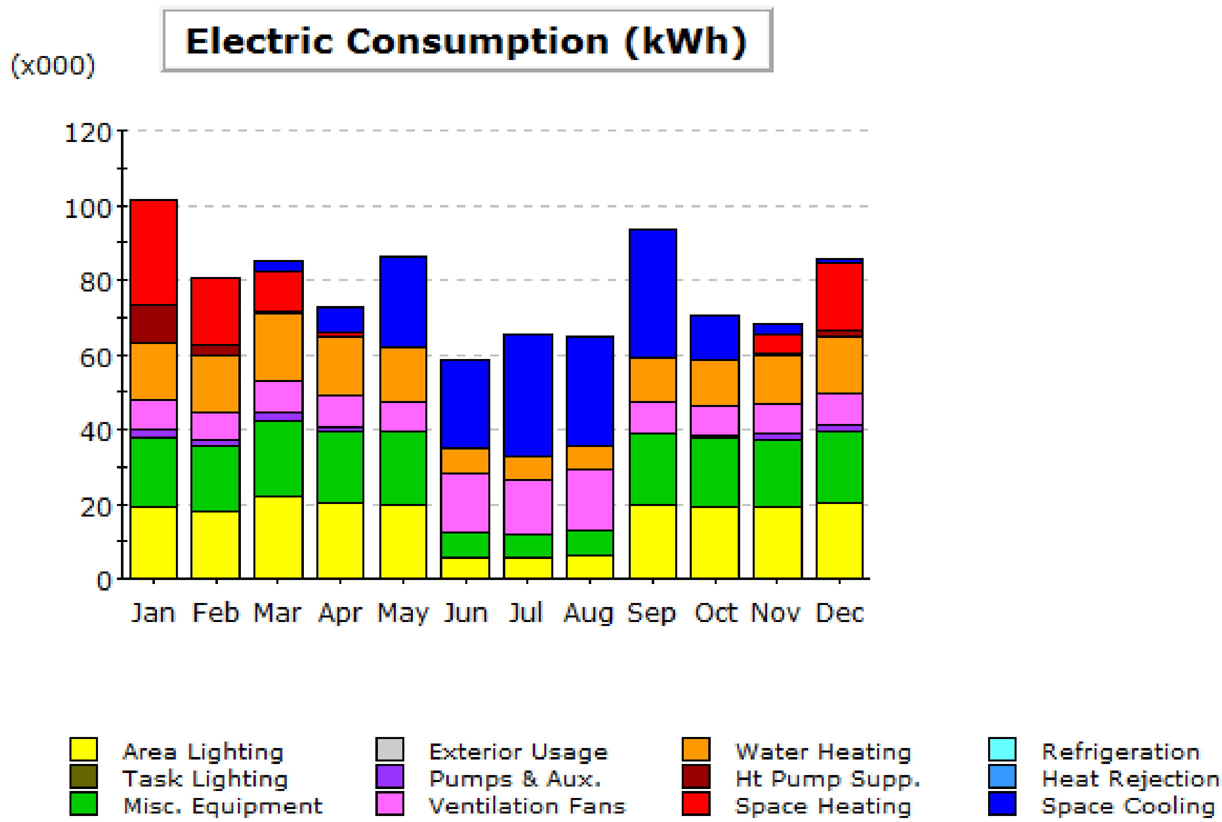
Figure B.8. Simulation when both are applied with 50% profile (Las Vegas)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.1	0.3	2.9	6.9	32.2	21.4	33.4	27.6	46.6	14.0	3.9	1.2	190.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	46.8	31.6	21.5	4.4	0.1	0.0	0.1	0.1	0.1	0.6	12.0	32.6	149.9
HP Supp.	20.4	7.3	2.1	0.1	-	-	-	-	-	0.0	0.8	5.2	36.0
Hot Water	28.0	27.3	32.6	29.4	27.0	6.8	6.0	6.3	21.8	22.1	23.8	27.3	258.4
Vent. Fans	9.7	9.1	10.8	10.2	10.0	19.6	18.0	20.4	9.9	9.7	9.5	10.2	147.1
Pumps & Aux.	1.9	1.8	1.8	1.4	0.1	-	-	-	0.0	0.5	1.5	1.7	10.6
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	144.6	112.9	114.1	91.6	108.6	60.2	69.6	67.2	117.5	84.8	88.9	117.6	1,177.5

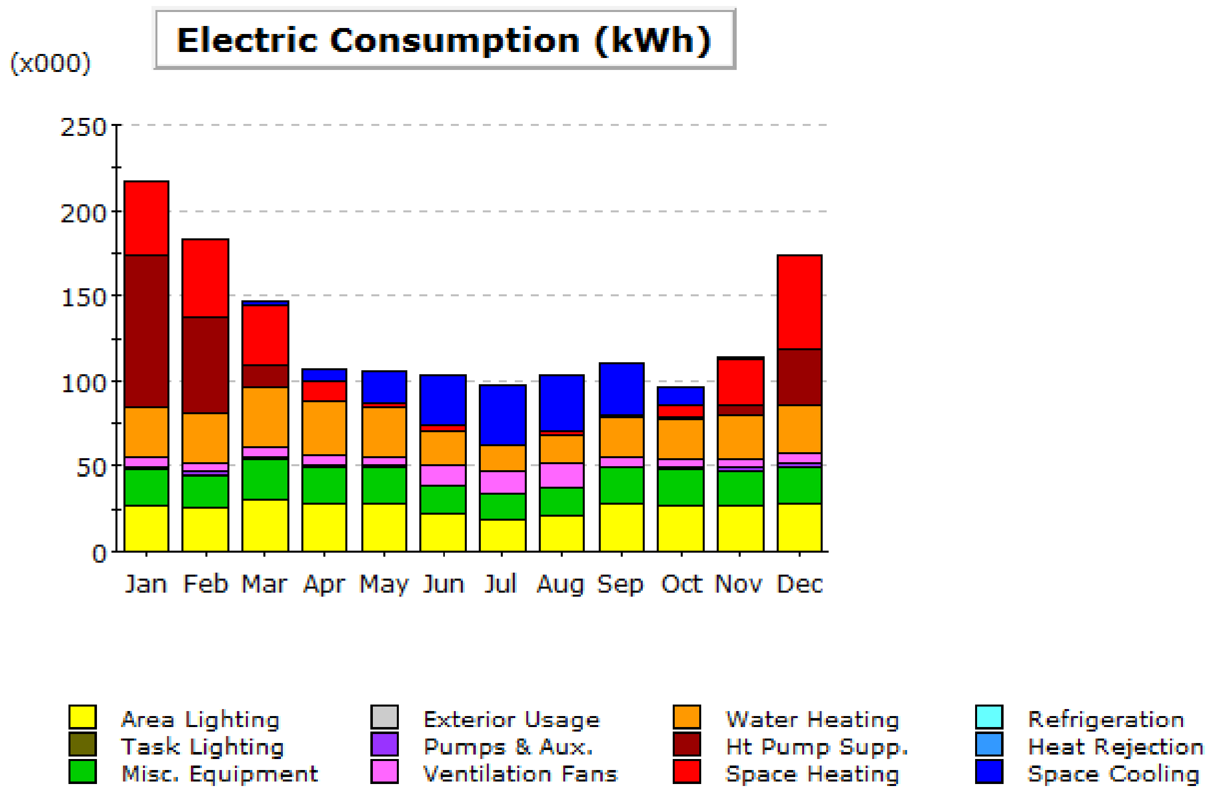
Figure B.9. Simulation for *Baseline* (New York)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.07	0.20	2.34	6.69	24.24	23.45	32.47	29.20	34.33	11.96	2.69	0.72	168.36
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	28.34	18.06	10.66	0.89	0.07	0.03	0.03	0.03	0.15	0.19	5.11	18.04	81.59
HP Supp.	9.93	2.57	1.00	0.03	-	-	-	-	-	0.00	0.34	2.05	15.92
Hot Water	15.61	15.01	17.70	16.03	14.62	6.75	6.03	6.30	11.87	12.29	13.19	15.14	150.54
Vent. Fans	7.88	7.35	8.75	8.23	8.08	15.87	14.59	16.54	8.05	7.88	7.70	8.23	119.14
Pumps & Aux.	1.97	1.89	1.93	1.38	0.10	-	-	-	0.02	0.45	1.61	1.84	11.20
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.55	17.41	20.70	19.19	19.21	6.52	6.44	6.76	19.11	18.55	18.36	19.29	190.09
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.23	18.13	21.74	20.07	19.99	5.82	5.64	6.04	19.95	19.23	19.07	20.11	195.01
Total	101.57	80.62	84.82	72.50	86.31	58.45	65.19	64.87	93.49	70.54	68.07	85.43	931.85

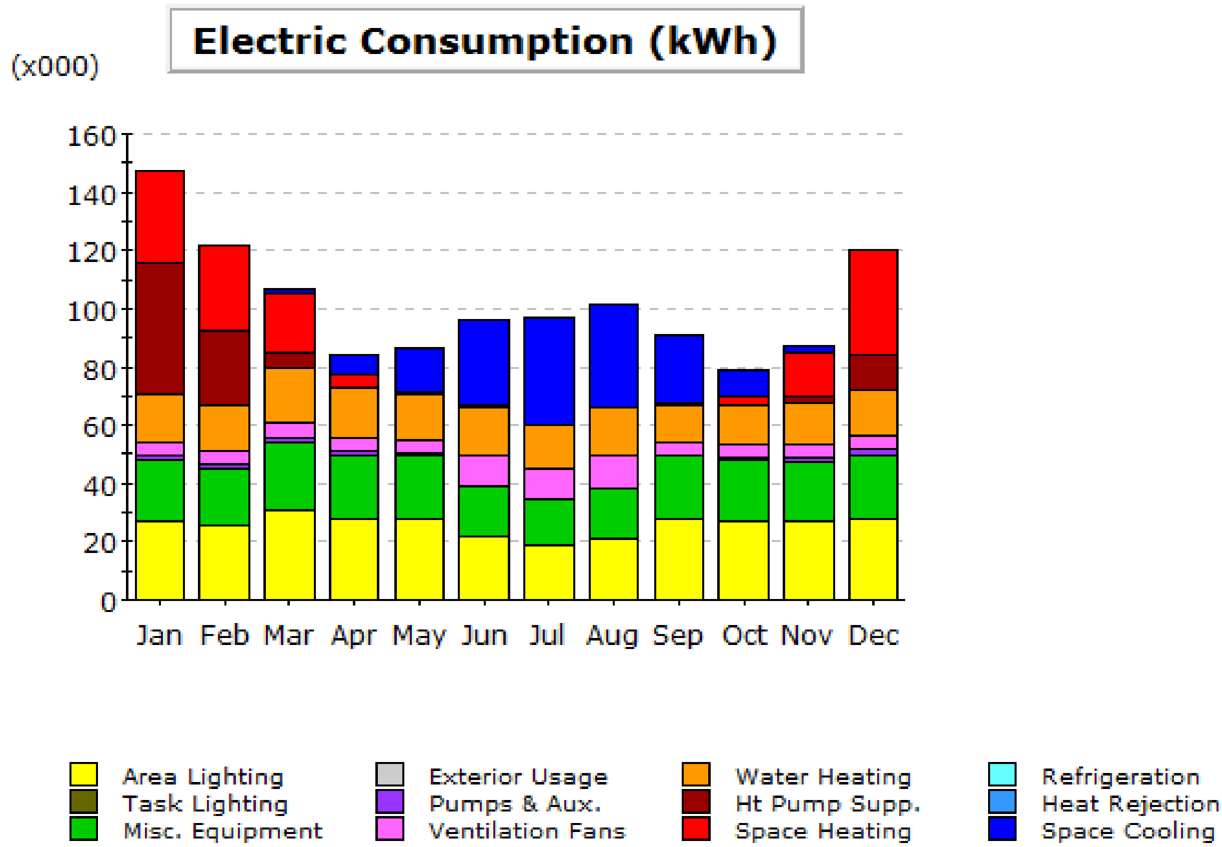
Figure B.10. Simulation when both are applied with 50% profile (New York)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.0	2.0	7.7	19.0	29.1	34.6	32.4	31.1	11.0	2.0	0.0	169.0
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	44.0	44.9	34.7	10.8	2.3	4.0	0.3	3.3	0.9	7.5	26.9	54.9	234.5
HP Supp.	88.9	57.3	13.5	1.0	0.1	0.0	-	-	-	0.5	5.9	32.5	199.6
Hot Water	29.8	29.1	34.7	31.2	28.8	19.2	15.0	16.0	23.4	23.7	25.5	29.1	305.5
Vent. Fans	5.2	4.9	5.8	5.4	5.3	11.6	12.7	13.5	5.3	5.2	5.1	5.4	85.3
Pumps & Aux.	2.0	1.7	1.8	1.3	0.7	0.1	0.0	0.1	0.3	1.2	1.6	1.8	12.7
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	20.9	19.6	23.3	21.7	21.7	17.3	15.5	16.9	21.6	20.9	20.7	21.8	241.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	26.8	25.3	30.5	28.0	28.0	21.8	18.8	21.1	27.9	26.8	26.7	28.0	309.7
Total	217.7	182.8	146.4	107.0	106.0	103.1	97.0	103.2	110.5	96.8	114.3	173.6	1,558.3

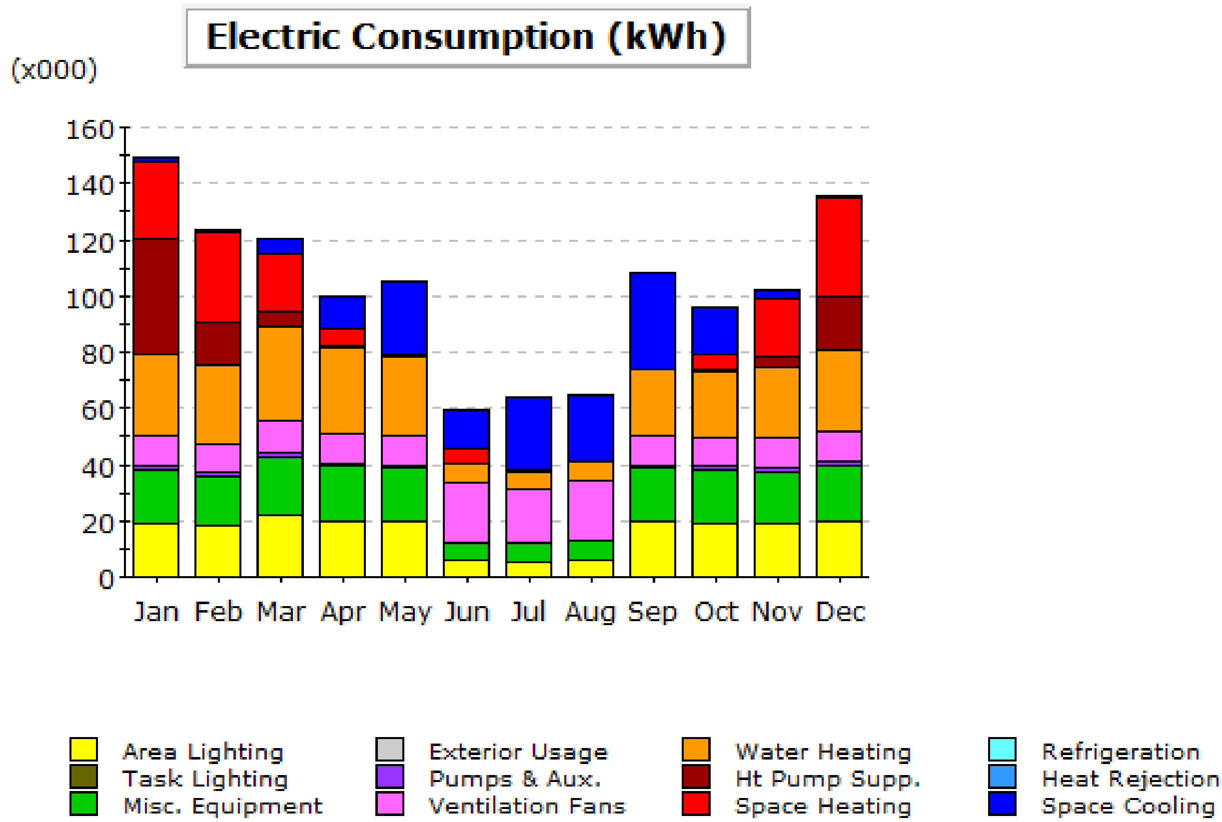
Figure B.11. Simulation for *Baseline* (Lansing)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.1	1.7	6.8	15.2	29.3	36.6	35.0	23.4	9.2	1.8	0.0	159.1
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	31.4	29.3	20.5	4.3	0.6	0.3	0.0	0.2	0.3	2.9	15.2	35.9	141.1
HP Supp.	45.1	25.8	5.1	0.4	0.0	0.0	-	-	-	0.2	2.4	11.9	90.9
Hot Water	16.4	15.9	18.7	16.8	15.5	16.8	15.0	16.0	12.7	13.0	14.0	16.0	186.9
Vent. Fans	4.5	4.2	5.0	4.7	4.6	10.0	11.1	11.7	4.6	4.5	4.4	4.7	74.2
Pumps & Aux.	2.1	1.8	1.9	1.3	0.7	0.2	0.0	0.1	0.3	1.3	1.7	1.9	13.5
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	20.9	19.6	23.3	21.7	21.7	17.3	15.5	16.9	21.6	20.9	20.7	21.8	241.9
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	26.8	25.3	30.5	28.0	28.0	21.8	18.8	21.1	27.9	26.8	26.7	28.0	309.7
Total	147.2	122.0	106.7	84.0	86.3	95.9	97.0	101.1	90.8	78.8	86.8	120.3	1,217.2

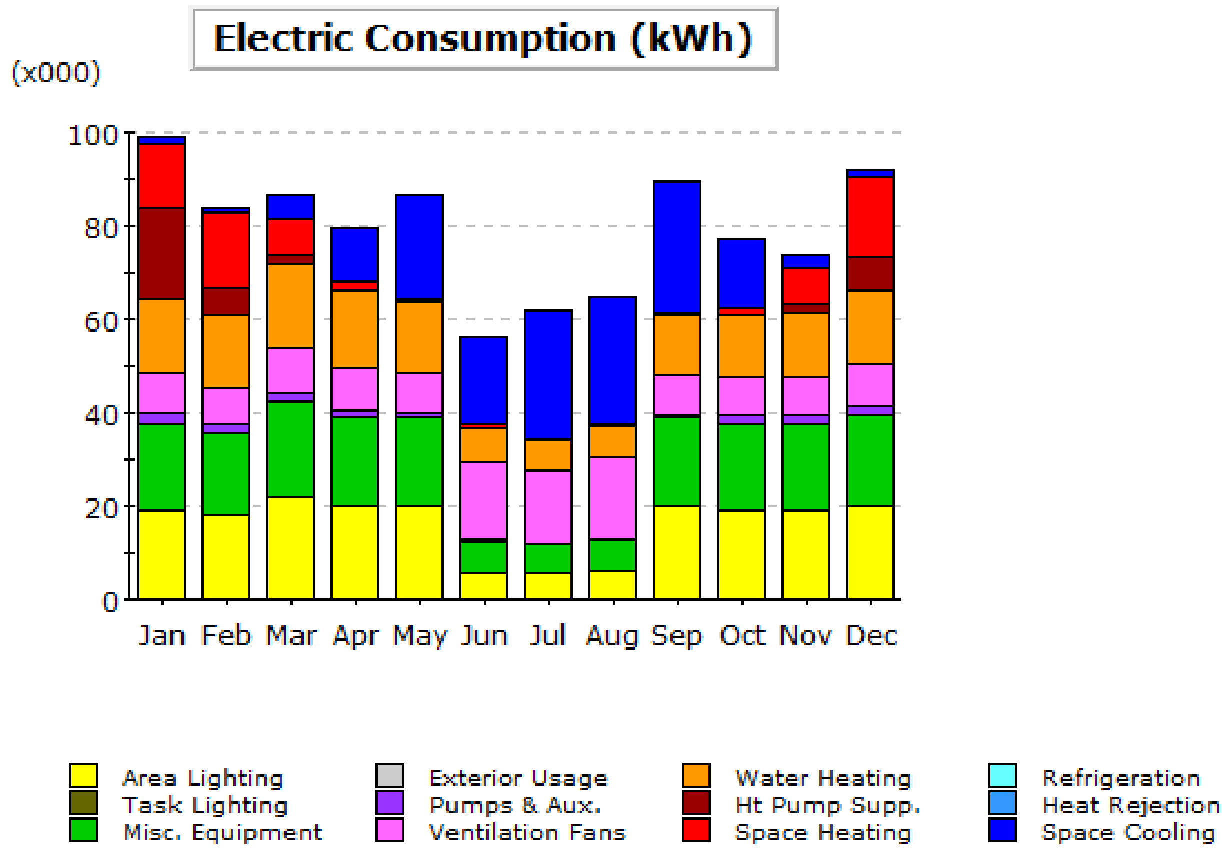
Figure B.12. Simulation when both are applied with 50% profile (Lansing)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	1.5	1.0	4.8	11.5	25.9	13.8	25.9	23.6	33.9	16.5	3.0	1.1	162.6
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	27.5	31.6	20.5	6.0	0.8	5.0	0.1	0.2	0.7	5.3	20.5	35.0	153.2
HP Supp.	41.0	15.7	5.4	0.6	0.0	-	-	-	0.0	0.7	3.9	18.7	86.2
Hot Water	29.0	28.2	33.6	30.4	28.2	7.2	6.4	6.7	23.4	23.7	25.2	28.6	270.5
Vent. Fans	10.4	9.7	11.5	10.8	10.6	20.9	19.2	21.8	10.6	10.4	10.1	10.8	156.7
Pumps & Aux.	2.0	1.7	1.8	1.3	0.8	0.2	-	0.0	0.5	1.5	1.8	1.9	13.5
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	149.1	123.5	120.1	99.9	105.5	59.4	63.7	65.1	108.2	95.7	102.0	135.6	1,227.8

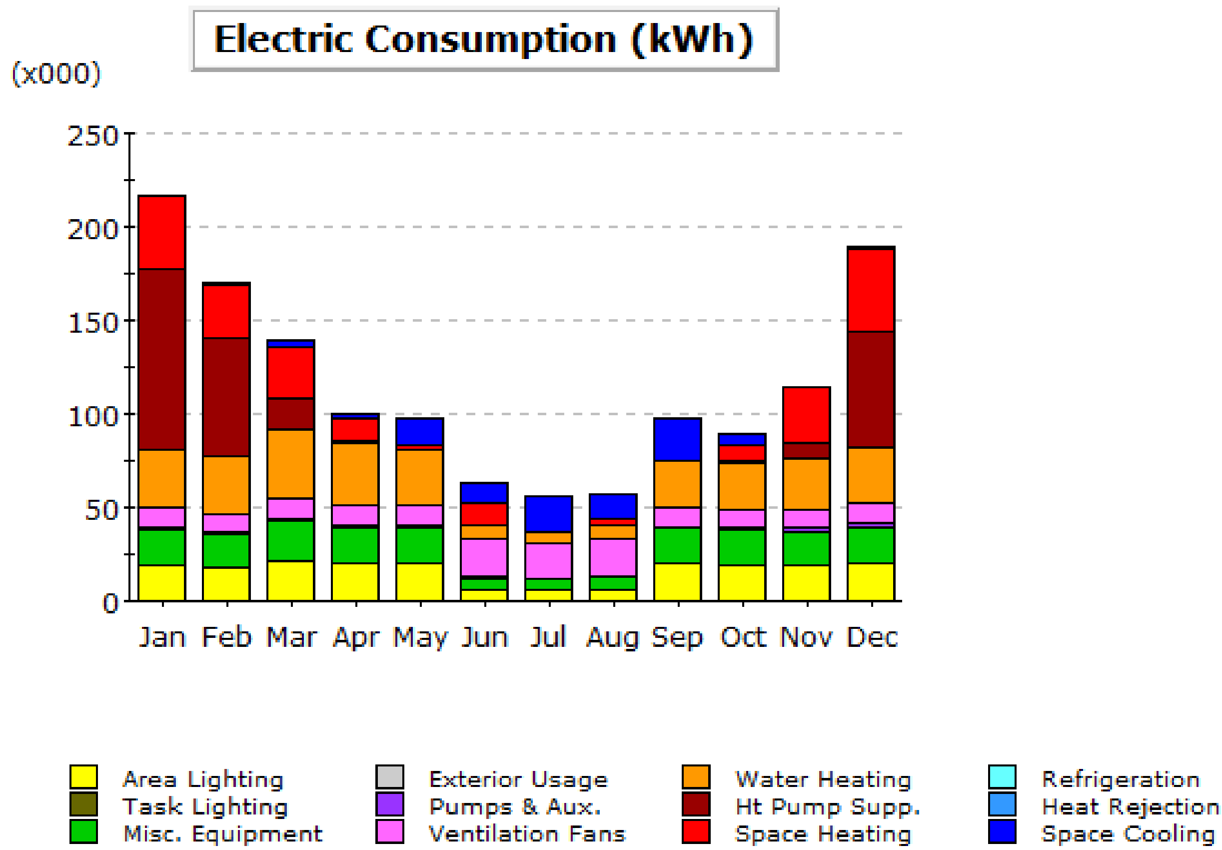
Figure B.13. Simulation for *Baseline* (Denver)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	1.52	1.13	5.18	11.75	22.52	18.53	27.83	27.44	28.20	14.79	2.98	1.35	163.20
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	13.71	16.19	7.43	1.76	0.32	0.76	0.08	0.12	0.39	1.32	7.78	17.07	66.92
HP Supp.	19.51	5.73	1.85	0.20	0.00	-	-	-	0.00	0.21	1.53	7.29	36.32
Hot Water	16.08	15.48	18.21	16.53	15.27	7.17	6.38	6.68	12.75	13.11	13.94	15.83	157.42
Vent. Fans	8.48	7.91	9.42	8.85	8.70	17.08	15.70	17.80	8.67	8.48	8.29	8.85	128.23
Pumps & Aux.	2.16	1.85	1.94	1.35	0.76	0.29	-	0.00	0.46	1.51	1.97	2.09	14.38
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.55	17.41	20.70	19.19	19.21	6.52	6.44	6.76	19.11	18.55	18.36	19.29	190.09
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.23	18.13	21.74	20.07	19.99	5.82	5.64	6.04	19.95	19.23	19.07	20.11	195.01
Total	99.22	83.82	86.46	79.71	86.76	56.17	62.07	64.85	89.52	77.20	73.93	91.89	951.58

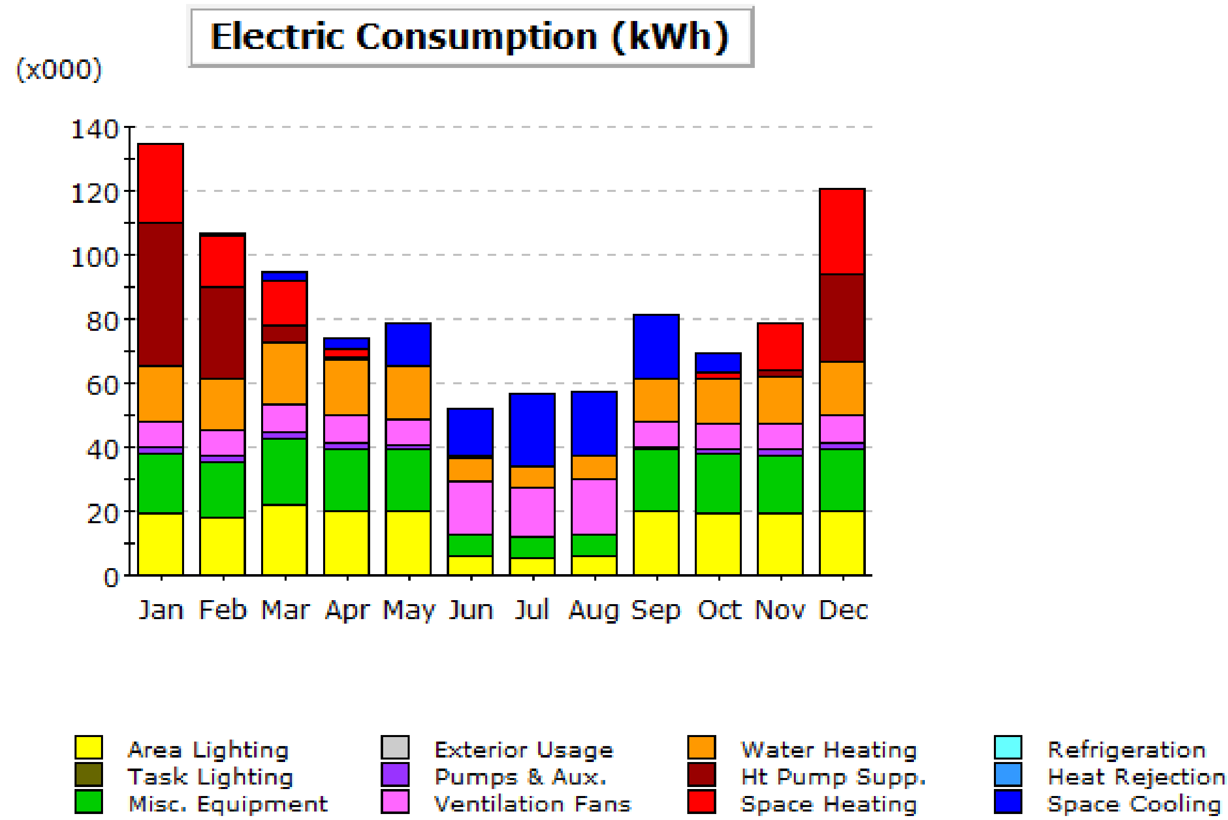
Figure B.14. Simulation when both are applied with 50% profile (Denver)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.4	2.7	2.5	13.4	10.7	18.3	13.7	22.4	6.0	0.3	0.0	90.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	39.5	28.9	28.3	12.6	2.9	11.4	0.1	2.6	0.7	9.0	30.4	45.1	211.4
HP Supp.	96.2	63.5	16.7	1.3	0.2	0.1	-	-	0.0	0.7	8.4	61.3	248.4
Hot Water	31.0	30.1	36.0	32.5	30.0	7.6	6.7	7.0	24.6	24.9	26.7	30.4	287.6
Vent. Fans	10.0	9.3	11.1	10.4	10.3	20.2	18.5	21.0	10.2	10.0	9.8	10.4	151.3
Pumps & Aux.	2.1	1.9	1.8	1.8	1.3	0.3	0.1	0.1	0.7	1.5	1.8	2.0	15.2
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	216.6	169.7	138.9	100.4	97.2	62.7	55.8	57.2	97.6	89.9	114.8	188.7	1,389.4

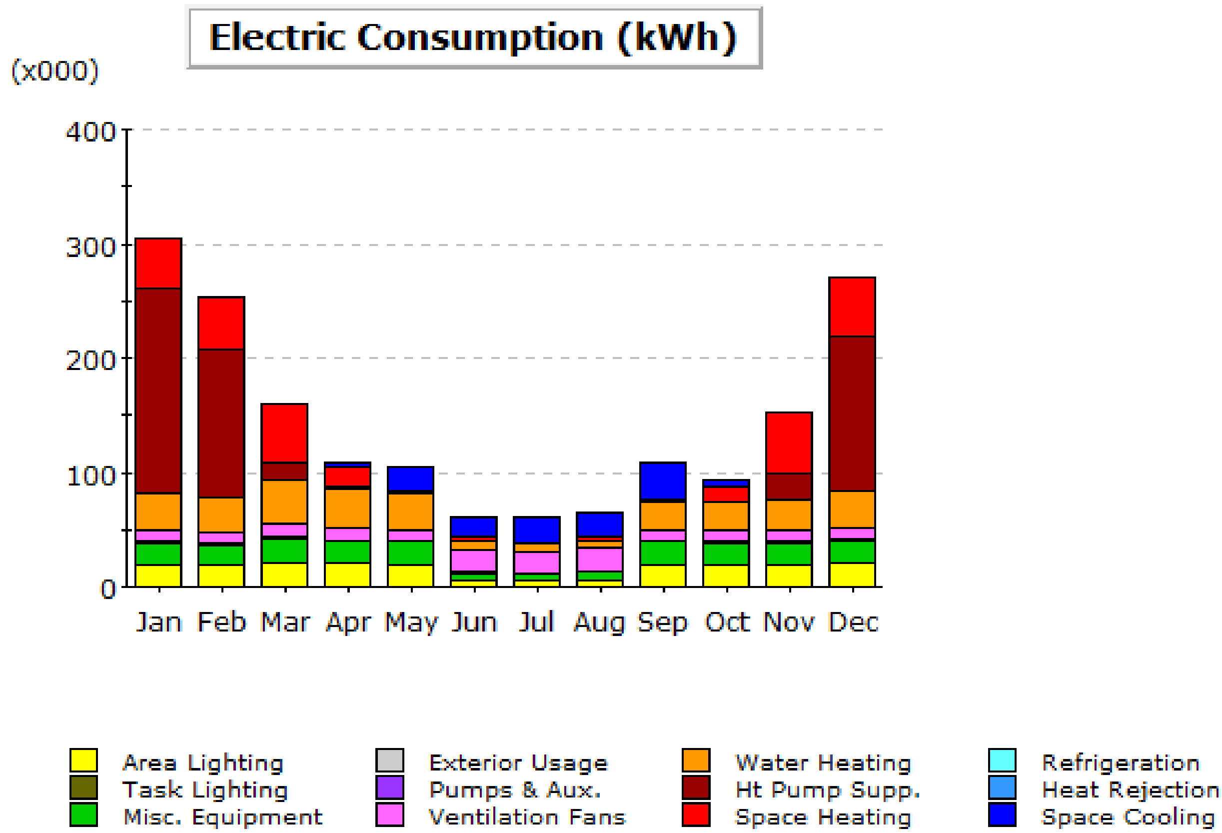
Figure B.15. Simulation for *Baseline* (Helena)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.3	2.5	3.3	12.9	14.6	22.8	19.9	19.9	5.9	0.4	0.1	102.5
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	24.7	16.1	14.2	2.9	0.3	0.5	0.1	0.0	0.1	1.8	14.2	26.7	101.6
HP Supp.	44.5	28.4	5.1	0.3	0.0	0.0	-	-	0.0	0.1	2.2	26.8	107.4
Hot Water	17.3	16.5	19.5	17.7	16.3	7.6	6.7	7.0	13.4	13.8	14.7	16.9	167.4
Vent. Fans	8.2	7.6	9.1	8.5	8.4	16.4	15.1	17.1	8.3	8.2	8.0	8.5	123.3
Pumps & Aux.	2.1	2.0	1.9	2.0	1.3	0.6	0.1	0.1	0.7	1.7	2.0	2.1	16.5
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	134.5	106.4	94.7	73.9	78.4	52.0	56.8	57.0	81.4	69.2	78.9	120.4	1,003.8

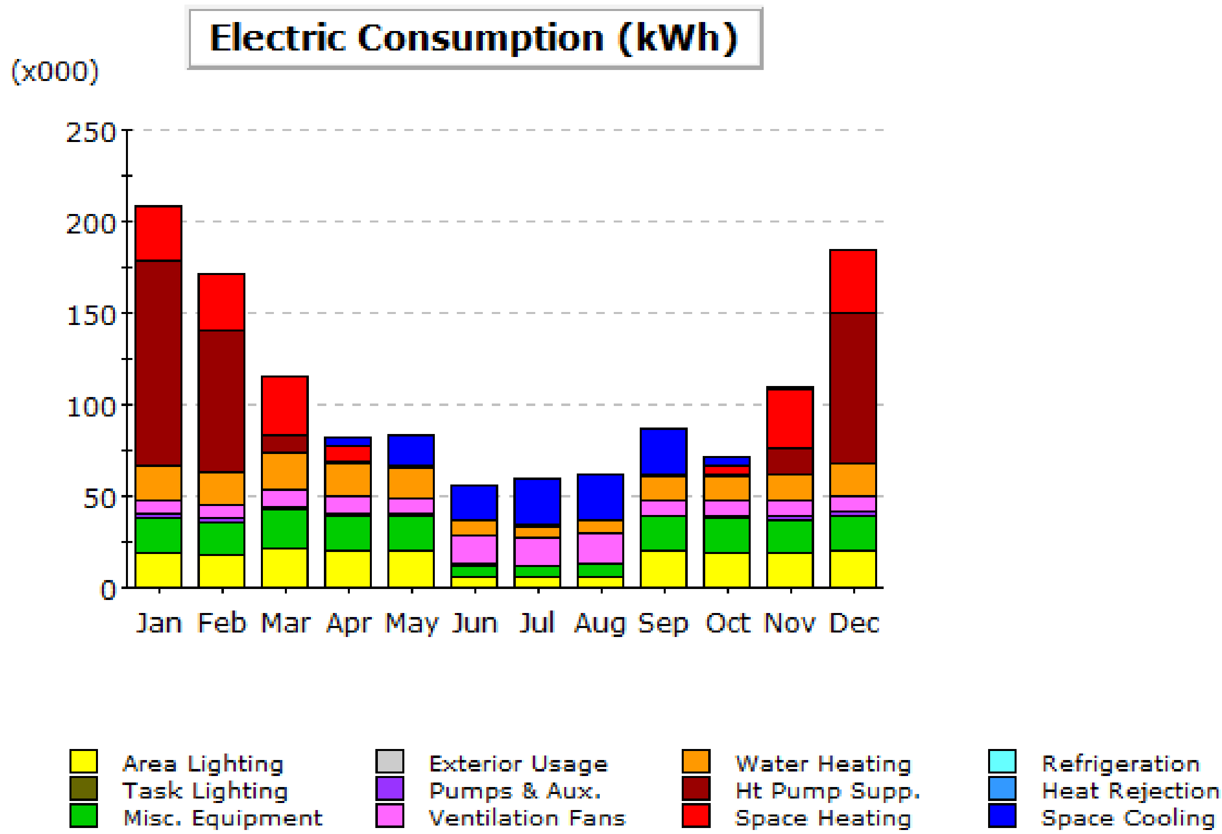
Figure B.16. Simulation when both are applied with 50% profile (Helena)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.0	0.1	5.3	21.1	15.5	23.2	21.8	32.0	5.6	0.3	-	125.1
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	43.2	46.3	50.9	16.9	2.4	4.4	0.3	2.4	2.4	12.1	52.6	50.7	284.6
HP Supp.	179.4	128.3	15.2	1.9	0.1	0.0	-	-	0.1	0.8	22.7	135.5	484.0
Hot Water	32.6	31.9	38.0	34.1	31.0	7.6	6.7	7.0	24.3	24.9	27.2	31.6	296.8
Vent. Fans	9.9	9.3	11.0	10.4	10.2	20.0	18.4	20.8	10.1	9.9	9.7	10.4	150.0
Pumps & Aux.	2.2	1.9	1.9	1.6	1.0	0.2	0.0	0.1	0.7	1.4	1.9	2.1	15.2
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	305.1	253.2	159.5	109.5	104.9	60.1	60.7	64.9	108.8	92.5	151.9	269.6	1,740.8

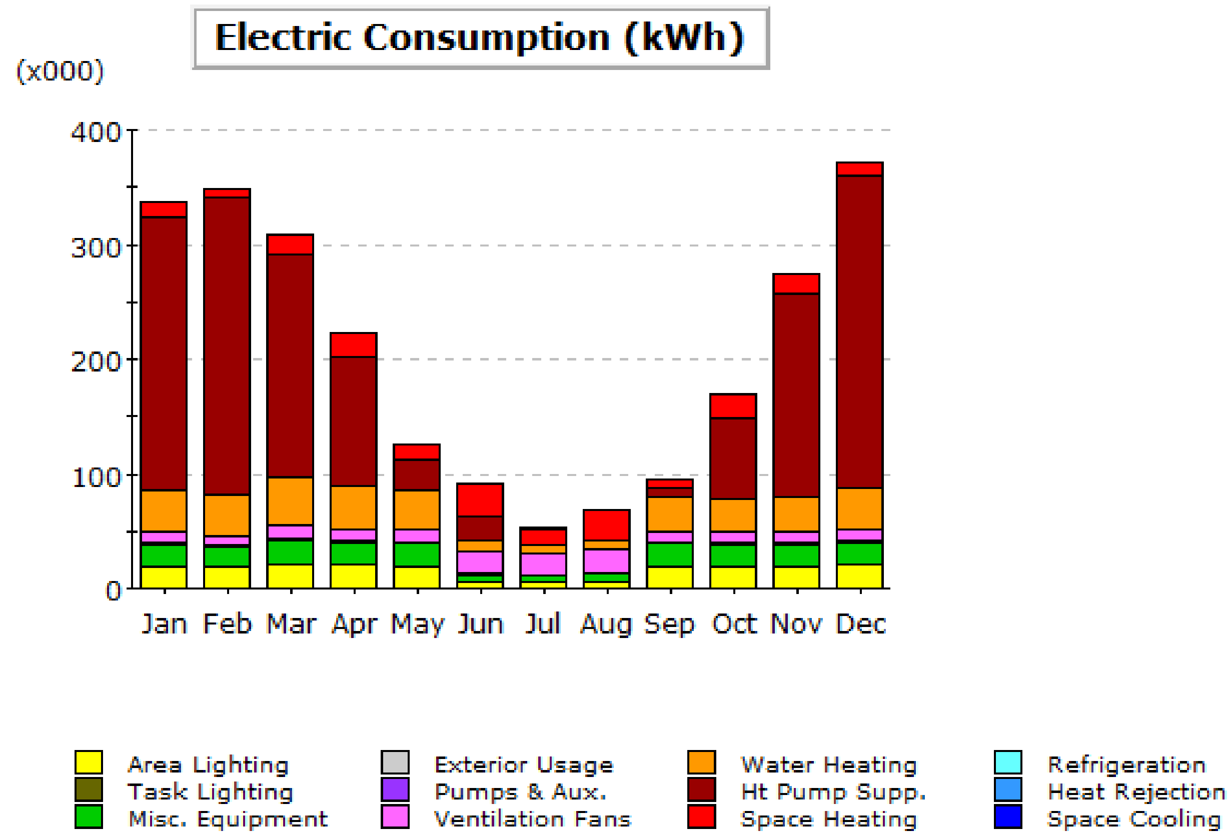
Figure B.17. Simulation for *Baseline* (Fargo)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	0.0	0.0	0.2	4.0	16.8	19.3	25.0	25.0	24.5	4.5	0.2	0.0	119.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	30.1	31.2	32.1	8.7	1.0	0.7	0.2	0.4	1.0	5.0	33.2	34.4	178.0
HP Supp.	111.9	77.7	9.0	1.0	0.0	0.0	-	-	0.0	0.3	13.2	82.7	295.9
Hot Water	18.1	17.5	20.5	18.5	16.7	7.6	6.7	7.0	13.3	13.8	15.1	17.6	172.5
Vent. Fans	8.1	7.5	9.0	8.4	8.3	16.3	15.0	17.0	8.3	8.1	7.9	8.4	122.2
Pumps & Aux.	2.3	2.0	2.1	1.7	0.9	0.3	0.0	0.2	0.7	1.6	2.0	2.2	15.9
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	208.3	171.5	115.2	81.6	83.0	56.5	59.0	62.3	86.8	71.0	109.1	184.7	1,289.0

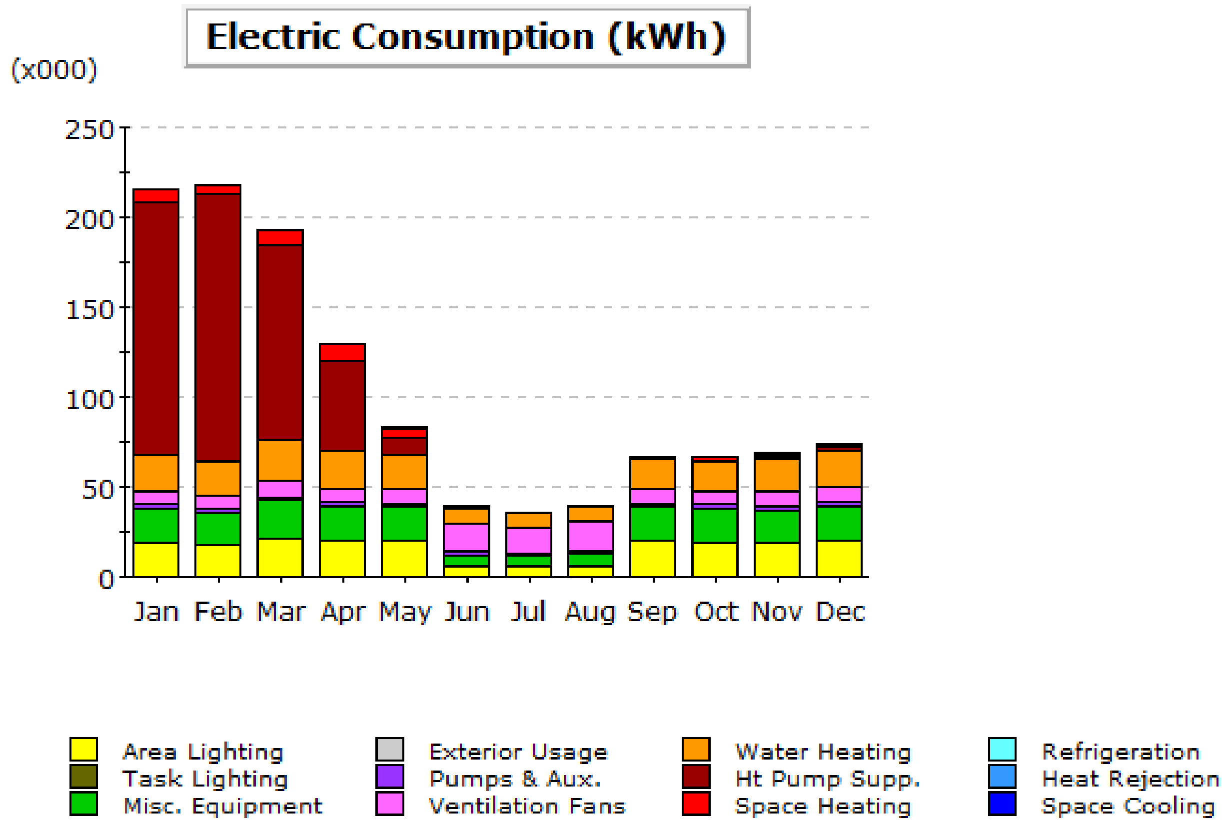
Figure B.18. Simulation when both are applied with 50% profile (Fargo)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	-	0.0	0.0	0.7	0.1	0.4	0.0	1.1	0.0	-	-	2.4
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	12.8	7.7	16.6	19.9	12.9	28.4	14.0	26.8	7.7	19.8	17.8	10.6	195.0
HP Supp.	238.8	259.1	194.6	113.9	27.2	22.4	-	0.8	7.0	70.4	176.6	273.3	1,384.0
Hot Water	35.7	34.8	41.5	37.6	34.9	8.9	8.0	8.4	29.3	29.5	31.3	35.4	335.2
Vent. Fans	9.6	9.0	10.7	10.0	9.8	19.3	17.8	20.1	9.8	9.6	9.4	10.0	145.1
Pumps & Aux.	2.2	2.2	2.0	1.8	1.7	0.6	0.3	0.5	1.6	1.9	1.9	2.3	19.0
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	336.9	348.2	307.9	222.5	126.3	92.0	52.5	69.5	95.6	169.0	274.5	371.0	2,465.9

Figure B.19. Simulation for *Baseline* (Bethel)



Electric Consumption (kWh x000)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Space Cool	-	0.0	0.0	0.1	0.7	0.7	0.9	0.6	0.8	0.4	0.5	0.5	5.2
Heat Reject.	-	-	-	-	-	-	-	-	-	-	-	-	-
Refrigeration	-	-	-	-	-	-	-	-	-	-	-	-	-
Space Heat	6.7	4.0	8.5	9.2	4.2	0.5	0.1	0.3	0.8	1.5	1.0	0.3	37.0
HP Supp.	141.2	149.4	109.1	50.1	9.9	0.0	-	0.0	0.1	0.3	2.2	2.8	465.2
Hot Water	19.8	19.1	22.5	20.5	18.9	8.9	8.1	8.5	16.0	16.5	17.5	20.0	196.2
Vent. Fans	7.9	7.3	8.7	8.2	8.1	15.8	14.5	16.5	8.0	7.9	7.7	8.2	118.8
Pumps & Aux.	2.3	2.2	2.1	1.9	1.8	1.4	0.5	1.2	1.8	2.3	2.3	2.5	22.3
Ext. Usage	-	-	-	-	-	-	-	-	-	-	-	-	-
Misc. Equip.	18.5	17.4	20.7	19.2	19.2	6.5	6.4	6.8	19.1	18.5	18.4	19.3	190.1
Task Lights	-	-	-	-	-	-	-	-	-	-	-	-	-
Area Lights	19.2	18.1	21.7	20.1	20.0	5.8	5.6	6.0	19.9	19.2	19.1	20.1	195.0
Total	215.5	217.6	193.3	129.3	82.8	39.7	36.2	39.9	66.5	66.7	68.7	73.6	1,229.8

Figure B.20. Simulation when both are applied with 50% profile (Bethel)

Appendix C

Table 1

Annual Energy for Various Locations with different strategies been applied to HVAC System

Location	Old Standard	New Standard		DCV 75%	Save	DCV 50%	Save	Both 100%	Save	Both 75%	Save	Both 50%	Save
1A-Miami	1,577	1,560		1,432	8%	1,318	16%	1,544	1%	1,426	9%	1,311	16%
2A-Orlando	1,460	1,4460		1,310	9%	1,172	19%	1,417	2%	1,282	11%	1,146	21%
2A-Houston	1,440	1,421		1,311	9%	1,239	14%	1,392	3%	1,288	11%	1,214	16%
3B-Nevada	1,364	1,345		1,196	11%	1,096	19%	1,238	8%	1,137	15%	1,041	23%
4A-Greensboro	1,281	1,258		1,114	13%	1,009	20%	1,171	7%	1,076	15%	966	23%
5A-New York	1,196	1,178	*Baseline*	1,033	12%	932	21%	1,095	7%	995	16%	897	24%
5A-Michigan	1,179	1,558		1,326	15%	1,217	22%	1,415	9%	1,301	17%	1,192	24%
5B-Denver	1,253	1,228		1,047	15%	952	22%	1,090	11%	997	19%	907	26%
6B-Helena	1,401	1,389		1,115	20%	1,004	28%	1,187	15%	1,076	23%	969	30%
7-Fargo	1,765	1,741		1,429	18%	1,289	26%	1,532	12%	1,384	21%	1,242	29%
8-Bethel	2,490	2,466		1,853	25%	1,230	50%	2,058	17%	1,850	25%	1,226	50%